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Site Response in Las Vegas Valley, Nevada from NTS Explosions and Earthquake Data

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Abstract—We report site response in Las Vegas Valley (LVV) from historical recordings of Nevada Test Site (NTS) nuclear explosions and earthquake recordings from permanent and temporary seismic stations. Our data set significantly improves the spatial coverage of LVV over previous studies, especially in the northern, deeper parts of the basin. Site response at stations in LVV was measured for frequencies in the range 0.2–5.0 Hz using Standard Spectral Ratios (SSR) and Horizontal-Vertical Spectral Ratios (HVR). For the SSR measurements we used a reference site (approximately NEHRP B "rock" classification) located on Frenchman Mountain outside the basin. Site response at sedimentary sites is variable in LVV with average amplifications approaching a factor of 10 at some frequencies. We observed peaks in the site response curves at frequencies clustered near 0.6, 1.2 and 2.0 Hz, with some sites showing additional lower amplitude peaks at higher frequencies. The spatial pattern of site response is strongly correlated with the reported depth to basement for frequencies between 0.2 and 3.0 Hz, although the frequency of peak amplification does not show a similar correlation. For a few sites where we have geotechnical shear velocities, the amplification shows a correlation with the average upper 30-meter shear velocities, V_{30}. We performed two-dimensional finite difference simulations and reproduced the observed peak site amplifications at 0.6 and 1.2 Hz with a low velocity near-surface layer with shear velocities 600–750 m/s and a thickness of 100–200 m. These modeling results indicate that the amplitude and frequencies of site response peaks in LVV are strongly controlled by shallow velocity structure.

Key words: Site response, strong ground motion, basin response.

Introduction

The city of Las Vegas, Nevada is situated in the Las Vegas Valley (LVV), a broad northwest-southeast trending sedimentary basin within the central basin and range province (Fig. 1). The basin was formed by extensional tectonics (WERNICKE *et al.*,

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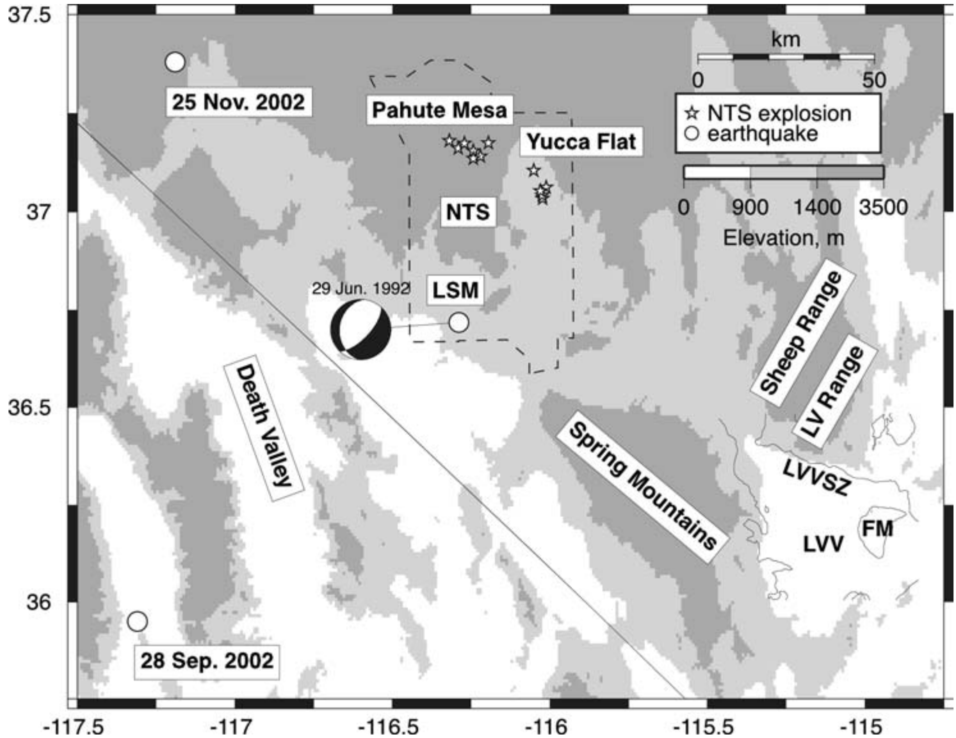

Figure 1
Map of southern Nevada showing Las Vegas Valley (LVV), the Nevada Test Site (NTS) and regional tectonic/geologic features (LVVSZ = LVV Shear Zone; FM = Frenchman Mountain). NTS nuclear explosions (stars), earthquakes (circles) considered in this study are shown. Focal mechanism of the Little Skull Mountain (LSM) earthquake is also shown (WALTER, 1993).

1988) and is filled with Tertiary sediments in the deeper sections and Quaternary alluvial and lake-bed sediments at the surface (TABOR, 1982). The basin is bounded on the north by the Las Vegas Valley Shear Zone (LVVSZ) and the Las Vegas Range, on the east by Frenchman Mountain and on the west by the Spring Mountains. LANGENHEIM *et al.* (2001a,b) reported the geometry of the basin and the LVVSZ using gravity and seismic reflection data. They estimated the maximum depth to bedrock to be nearly 5 km (Fig. 2a), although the definitions of geologic units and the ages of sedimentary sequences are poorly known. Significant seismic hazard in Las Vegas is indicated by its location in a deep sedimentary basin, surface sedimentary deposits and the proximity of major earthquake faults. Furthermore, Las Vegas is one of the fastest growing urban areas in the United States. These factors indicate that the response of LVV to seismic ground motion deserves thorough investigation.

As part of an effort to measure ground motions in southern Nevada from nuclear testing a network of seismic stations was operated by Blume and Associates for the Atomic Energy Commission (AEC) and later the Department of Energy (DOE). An early report by DAVIS and LYNCH (1970) studied the seismic response of Las Vegas to underground nuclear explosions at the Nevada Test Site (NTS). DAVIS and LYNCH (1970) reported variable seismic response within the central section of present-day Las Vegas (near Las Vegas Boulevard or "The Strip"), with amplifications of up to a factor of four in peak ground motion. However, due to limited data at the time, emphasis was placed on just two sites (SQPK and SE6, Fig. 2b).

Two published studies investigated seismic ground motion in LVV. MURPHY and HEWLETT (1975) used recordings from six NTS nuclear explosions to determine ground motion amplification within Las Vegas at 26 sites, concentrated within

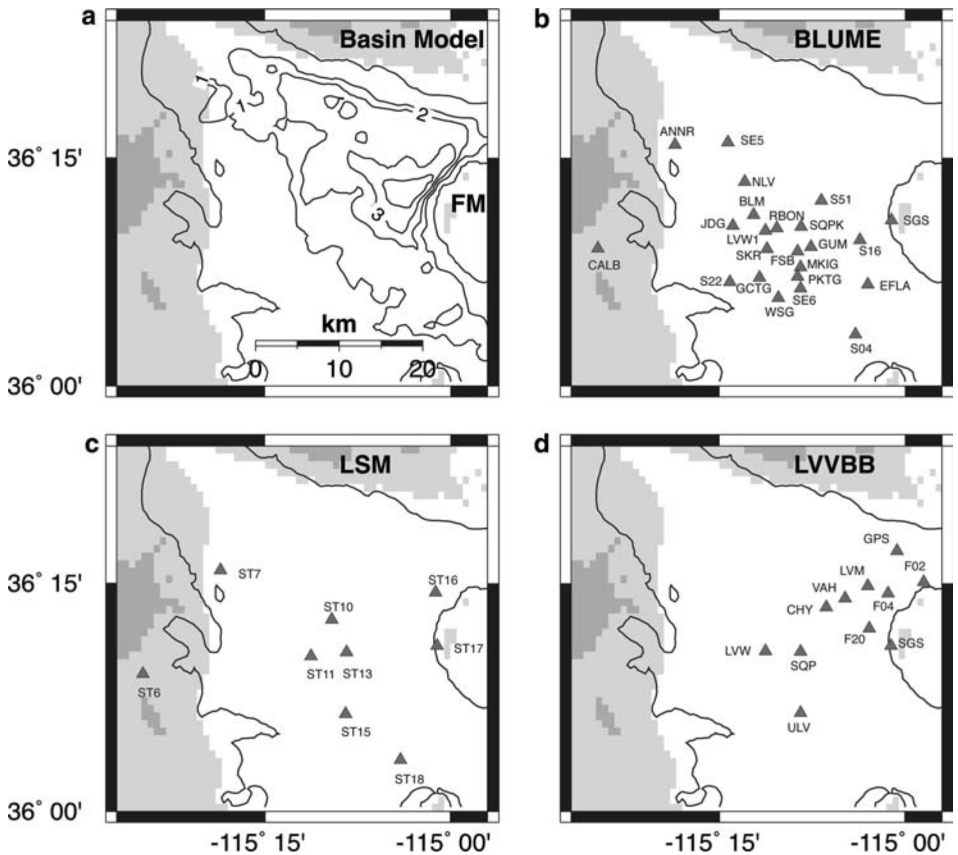

Figure 2

Map of Las Vegas Valley showing (a) the basin model from LANGENHEIM *et al.* (2001a) and seismic stations from various networks used in this study (triangles): (b) BLUME-NTS; (c) BLUME-LSM; and (d) LVVBB. In (b)–(d) 0.1-km contour showing depth to basement by LANGENHEIM *et al.* (2001b).

present-day central Las Vegas (Las Vegas Boulevard). Their data set was comprised of different explosions and sites than ours, but we have some sites in common. They reported a correlation between low-frequency site response and inferred alluvium thickness, based on Rayleigh wave ellipticity. The greatest amplification was observed at frequencies 0.33–0.22 Hz (3.3–4.5 s periods) where the amplification was nearly a factor of 8. However, they used a reference site within the basin on the western side of downtown (Site 801, Fig. 1 from the paper by MURPHY and HEWLETT, 1975). Ideally a reference site should be located on hard rock with little or no site response in order to obtain accurate estimates of basin site amplification (e.g., STEIDL *et al.*, 1996). Therefore the reported amplifications could be greater depending on the frequency-dependent site response at Site 801. Without the access to their data set we cannot assess possible biases in their results relative to our data set.

SU *et al.* (1998) reported ground motion and site response at nine sites in a broader area of LVV from the M_W 5.6 June 29, 1992 Little Skull Mountain (LSM) earthquake (Fig. 2c shows the sites considered). That event was located on the southwestern corner of NTS with similar although slightly shorter paths compared to NTS explosions (Fig. 1). They reported amplifications greater than a factor of ten at sedimentary sites in the Valley relative to the average spectral amplitude at two reference sites (ST6 and ST17) on the Valley's periphery. They also reported that maximum amplification generally occurred for periods below 1 Hz (Fig. 8 from the paper by SU *et al.*, 1998). By using data from co-located sites, SU *et al.* (1998, Fig. 10) showed that the analysis of MURPHY and HEWLETT (1975) underpredicts the site response in Las Vegas relative to a reference site on the Valley's periphery. SU *et al.* (1998) used site response to predict ground motion in LVV from large scenario earthquakes on the Death Valley Fault system.

In this article we report site response in LVV from historical nuclear tests and earthquake recordings. The data set has more complete spatial coverage than previous studies and provides a more comprehensive study of site response in Las Vegas Valley. We obtained previously unanalyzed waveform data from thirteen nuclear explosions at many Blume and Associates sites in LVV and all the LSM data analyzed by SU *et al.* (1998). We also deployed twelve temporary stations to provide improved coverage of LVV, including the populated and previously unsampled northern areas of LVV and Nellis Air Force Base. We benefit from more complete information on the depth-to-basement (LANGENHEIM *et al.*, 2001a,b) and preliminary reports of geotechnical velocity structure. Site response is modeled with two-dimensional finite difference simulations for frequencies up to 1.5 Hz. Results indicate that shallow ($\leq$ 200 m) sedimentary velocity structure has a strong influence on ground motion amplification, particularly with regard to the observed site response peaks around 0.6 and 1.2 Hz. The following sections describe the data, site response analysis and modeling. We conclude with a summary and discussion.

Ground Motion Data

The data used in this study come from three sources: NTS explosions recorded at the Blume and Associates Seismic Safety Program network (which we will refer to as BLUME-NTS); the June 29, 1992 Little Skull Mountain earthquake recorded by the Blume network (which we will refer to as BLUME-LSM) and our own temporary deployment of seismometers — the Las Vegas Valley Broadband Deployment (which we will refer to as LVVBB). These data sets are described below.

The Blume and Associates Seismic Safety Program network was installed in the early 1960s and operated until the last nuclear test in 1992. Stations were located throughout southern Nevada and eastern California. Data were used to understand ground motions from nuclear explosions at NTS and the impact on buildings and structures. The data were recorded on three-component analog strong motion accelerographs, with the specific network configuration and instrumentation systems evolving over time. The ground motions were digitized at 200 samples per second. We found these records to have useful signals in the frequency band 0.2–5 Hz. The instrument corrected ground motion time series from legacy NTS shots were read from their archival ASCII format and converted to Seismic Analysis Code (SAC2000) format (GOLDSTEIN *et al.*, 2003).

All seismograms for NTS explosions recorded in LVV were previewed and P and S waves were picked. We collected records for thirteen nuclear test explosions recorded at 29 sites in LVV. However, only four explosions (BARNWELL, BODIE, COTTAGE and GASCON) were recorded at our reference site, SGS, located on the flank of Frenchman Mountain (Fig. 2b). Table 1 details all the nuclear explosions considered in this study, taken from SPRINGER *et al.* (2002). None of the explosion data which we analyzed were included in the analysis of MURPHY and HEWLETT (1975). Explosion events were located in the Pahute Mesa and Yucca Flat areas of NTS (Fig. 1). Both source regions have very similar paths from NTS to LVV. Emplacement conditions and near-source geology in Yucca Flat and Pahute Mesa are different and this results in different far-field seismic response (e.g., WALTER *et al.*, 1995). The events tend to be quite large, with teleseismic body-wave magnitudes, m_b, between 5.3 and 5.9. Figure 2b shows a map of the 23 BLUME-NTS sites in the LVV that recorded at least one explosion with the SGS reference site. We also obtained data for the 29 June, 1992 Little Skull Mountain earthquake on NTS recorded by the Blume and Associates network and analyzed by SU *et al.* (1998). These sites (BLUME-LSM) are shown in Figure 2c. Station ST17 (SU *et al.*, 1998) is co-located with the BLUME station SGS.

The Las Vegas Valley Broadband Deployment (LVVBB) recorded continuous weak motions from local, regional and teleseismic events between September 2002 and January 2003. The eleven stations, shown in Figure 2d, were configured to sample the northern parts of LVV along the densely populated Las Vegas Boulevard/ I–15 corridor as well as to overlap sites from the BLUME and LSM data sets. We

Table 1

*Event information for the NTS nuclear explosions (*Springer et al., 2002) *and earthquakes used in this study*

Name	Date	Time (UTC)	Region	Latitude	Longitude	Depth (km)	Magnitude*	Yield (kiloton)
BOXCAR	1968 Apr 26	15:00:00.07	Pahute	37.295	−116.457	1.158	–	1300
HANDLEY	1970 Mar 26	19:00:00.20	Pahute	37.300	−116.535	1.209	–	> 1000
MUENSTER	1976 Jan 03	19:15:00.16	Pahute	37.297	−116.334	1.452	–	200–1000
FONTINA	1976 Feb 12	14:45:00.16	Pahute	37.271	−116.489	1.219	–	200–1000
JORNADA	1982 Jan 28	16:00:00.10	Yucca	37.091	−116.052	0.639	5.9	139
NEBBIOLO	1982 Jun 24	14:15:00.09	Pahute	37.236	−116.371	0.640	5.6	20–150
TURQUOISE	1983 Apr 14	19:05:00.12	Yucca	37.073	−116.047	0.533	5.7	< 150
MUNDO	1984 May 01	19:05:00.09	Yucca	37.106	−116.023	0.566	5.3	20–150
COTTAGE*	1985 Mar 23	18:30:00.08	Yucca	37.180	−116.090	0.515	5.3	20–150
GASCON*	1986 Nov 14	16:00:00.07	Yucca	37.100	−116.049	0.593	5.8	20–150
BODIE*	1986 Dec 13	17:50:05.08	Pahute	37.263	−116.413	0.635	5.5	20–150
TAHOKA	1987 Aug 13	14:00:00.09	Yucca	37.061	−116.046	0.639	5.9	20–150
BARNWELL*	1989 Dec 08	15:00:00.09	Pahute	37.231	−116.410	0.601	5.5	20–150
LSM*	1992 Jun 29	10:14:00.00	LSM	36.72	−116.30	11	5.4	–
LVVBB1*	2002 Sep 28	10:34:46.00	Coso	35.95	−117.31	15	4.1	–
LVVBB2*	2002 Nov 25	00:03:10.05	Goldfield	37.38	−117.19	7	3.9	–

* indicates events recorded at reference site SGS/ST17

deployed one station on the foot of Frenchman Mountain near the historical station SGS, although the area near SGS has been urbanized since the time of the Blume and Associates network. The LVVBB stations featured various instruments including Guralp CMG-3ESP, Guralp 40T and Geotech S-13 sensors. Reftek 72A-08 24-bit data loggers recorded data with GPS time at 40 samples per second. Two regional earthquakes were used for site response measurements (Fig. 1 and Table 1).

As an example of the BLUME-NTS data set, we show the north component velocity seismograms (band-pass filtered 0.1–10 Hz) for the BARNWELL explosion at six sites throughout the Valley (Fig. 3a). Amplitudes at the sites SGS and CALB, on the Valley's periphery, are the smallest, while amplitudes within the basin are largest, particularly at LVW, RBON, S51 and SE6. Note that the duration of elevated ground motion is quite long within the basin and the slower surface waves and coda tend to be longer period than the direct S wave. Such long duration and amplified ground motions within sedimentary basins are common and well reported. Note that accelerations from the largest NTS explosion (BOXCAR) in LVV were always below 20 cm/s^2 ($\sim$2% g) and would generally be considered weak motion. Figure 3b shows the velocity amplitude spectra (0.1–10 Hz) of the S wave and available pre-event noise windows for both horizontal components at the same sites as Figure 3a. Signal-to-noise ratios are quite high, generally greater than 10, for all shots and sites in the band 0.2–10 Hz. The BLUME-NTS accelerographs were band-limited at the low end between 0.1 and 0.2 Hz, making it difficult to use the long-period energy. The velocities on both horizontal components have similar

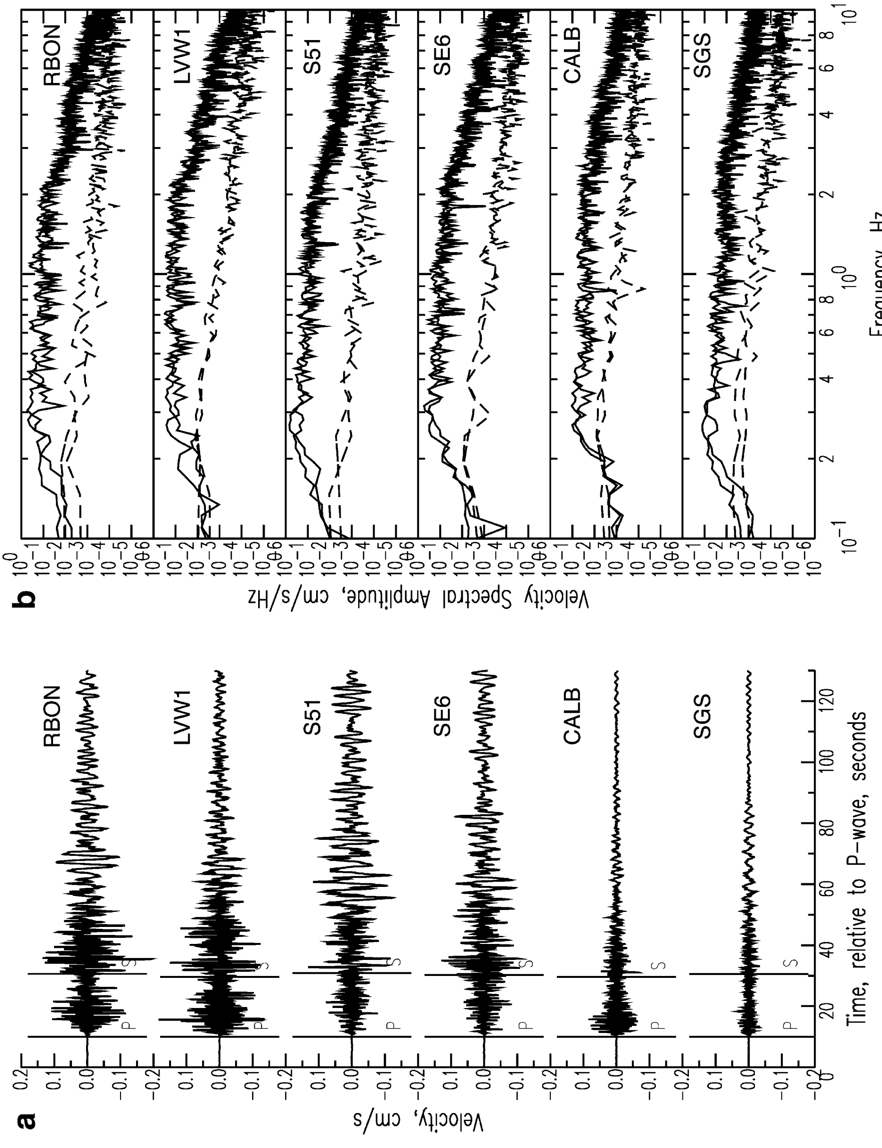

Figure 3
(a) North component velocity waveforms (filtered 0.1–10 Hz) for the BARNWELL nuclear test at a few sites in LVV. (b) Horizontal component velocity amplitude (solid) and noise (dashed) spectra for the waveforms shown in (a).

amplitudes. The peak amplitude occurs at around 0.2–0.4 Hz (2.5–5 s) for these stations. The raw amplitude spectra contain source, path and site effects. In order to measure site response we must remove source and path effects using both the explosion and earthquake data sets.

Site Response Methodology

Site response measurements seek to quantify the frequency-dependent amplification effects of shallow velocity structure and local geology at a recording site (see for example FIELD *et al.*, 2000; KAWASE, 2003 for reviews). Site response estimates must remove source and path propagation effects from observed ground motion. Several methods have been developed to estimate site response over the last several decades. Spectral ratios have been widely used when multiple observations of an event are recorded (e.g., BORCHERDT, 1970; BORCHERDT and GIBBS, 1976; KING and TUCKER, 1984; FIELD *et al.*, 1992). The Standard Spectral Ratio (SSR; BORCHERDT, 1970; BORCHERDT and GIBBS, 1976) uses the ratio of Fourier amplitude spectra of one site relative to a reference site. SAFAK (1997) gives a detailed analysis of site response measurement techniques when a pair of records is available, including alternatives to the SSR. Key to spectral ratio methods is the selection of the reference site, which ideally is located on hard rock and has little or no amplification relative to the motion input into the basin. The reference site must be close enough to sites of interest so that source and propagation effects are sufficiently similar and cancel when forming the spectral ratio. Studies have shown that hard rock sites can have amplification, deamplification due to tunnel and borehole effects, weathering of near-surface rock and/or topographic effects (TUCKER *et al.*, 1984; STEIDL *et al.*, 1996; YU and HAINES, 2003). If the shallow shear velocities or National Earthquake Hazards Reduction Program (NEHRP) soil profile types (BSSC, 1995, 1998) at the sites are known, they can be used to classify sites and identify reference site(s) (e.g., MARTIROSYAN *et al.*, 2003). Another class of site response estimation techniques requiring multiple stations is the Generalized Inversion Method. These techniques seek to simultaneously model source, propagation and site contributions to ground motion spectral amplitudes and can be used when event-station geometries sample different propagation paths (ANDREWS, 1986; BOATWRIGHT *et al.*, 1991; HARTZELL, 1992). Frequency-dependent S-wave coda amplitudes have been modeled in a similar fashion (PHILLIPS and AKI, 1986).

When recordings at a reference site are not available or only single station data are available, researchers have used the Horizontal-Vertical Spectral Ratio (HVR) technique. This technique was developed to study microtremor (NAKAMURA, 1989) and is also referred to as the receiver function technique (LANGSTON, 1979). Several recent studies have compared site response estimation methods (e.g., FIELD and JACOB, 1995; LACHET *et al.*, 1996; BONILLA *et al.*, 1997; RIEPL *et al.*, 1998). These studies generally report that spectral ratio and generalized inversion techniques yield similar site response estimates, but uncertainties can be different depending on the data weighting. These studies also report that HVR site response estimates result in similar peak response frequencies as two- or multiple-station methods, but amplifications are often lower than SSR estimates.

The stations considered in this study are in relatively close proximity (~30 km) considering that the explosions and earthquakes are at regional epicentral distances (110–235 km). The paths to Las Vegas stations exit the source region along very similar azimuths. For such geometries, source radiation pattern and propagation effects are common among recording stations. Our data are well suited for the SSR method as originally described by BORCHERDT (1970). Sites SGS/ST17 and CALB/ST06 are located outside of the deepest part of the sedimentary basin on the flanks of the Frenchman Mountain and the Spring Mountains, respectively (Fig. 2). These sites consistently observed the weakest ground motion for any given event (Fig. 3a). Geotechnical investigations (LUKE *et al.*, 2002; LIU *et al.*, 2004) indicate that the shallow shear velocities in the upper 30 meters at SGS/ST17 and CALB/ST06 are 695 and 889 m/s, respectively, at or above 760 m/s (NEHRP B, "rock"). This suggests that SGS and CALB are appropriate reference sites. Because SGS/ST17 was closer to our target sites and consistently had lower ground motions than CALB/ST06, we chose to use SGS/ST17 as our reference site. The CALB site is located in a small basin (Calico Basin) and is further from the central Las Vegas sites, making it less desirable. Our results are not significantly different when we used CALB/ST06 as the reference site, although amplifications above 1 Hz were slightly smaller when we used CALB as a reference site.

Site response was estimated with the Standard Spectral Ratio (BORCHERDT, 1970; BORCHERDT and GIBBS, 1976). Waveforms were selected based on visual inspection and signal-to-noise. We extracted three-component S-wave ground motions using windows of 60-second length and applied a 5% Hanning taper. Fourier amplitude spectra were measured on the two horizontal components. Noise amplitudes were computed from the available pre-P-wave window in a similar fashion. Signal-to-noise ratios were typically greater than ten, but because of a few exceptions, only data with signal amplitudes greater than three times the pre-event noise were used in the analysis. We computed the ratio of the root-mean-square spectral amplitude of the horizontal ground motions to estimate the site response between the k^{th} basin site relative to the reference site, j:

$$SR_k^j(f) = \frac{\sqrt{\left(A_k^n(f)\right)^2 + \left(A_k^e(f)\right)^2}}{\sqrt{\left(A_j^n(f)\right)^2 + \left(A_j^e(f)\right)^2}},$$

where superscripts n and e indicate north-south and east-west components, respectively. When multiple events were observed site response curves were averaged

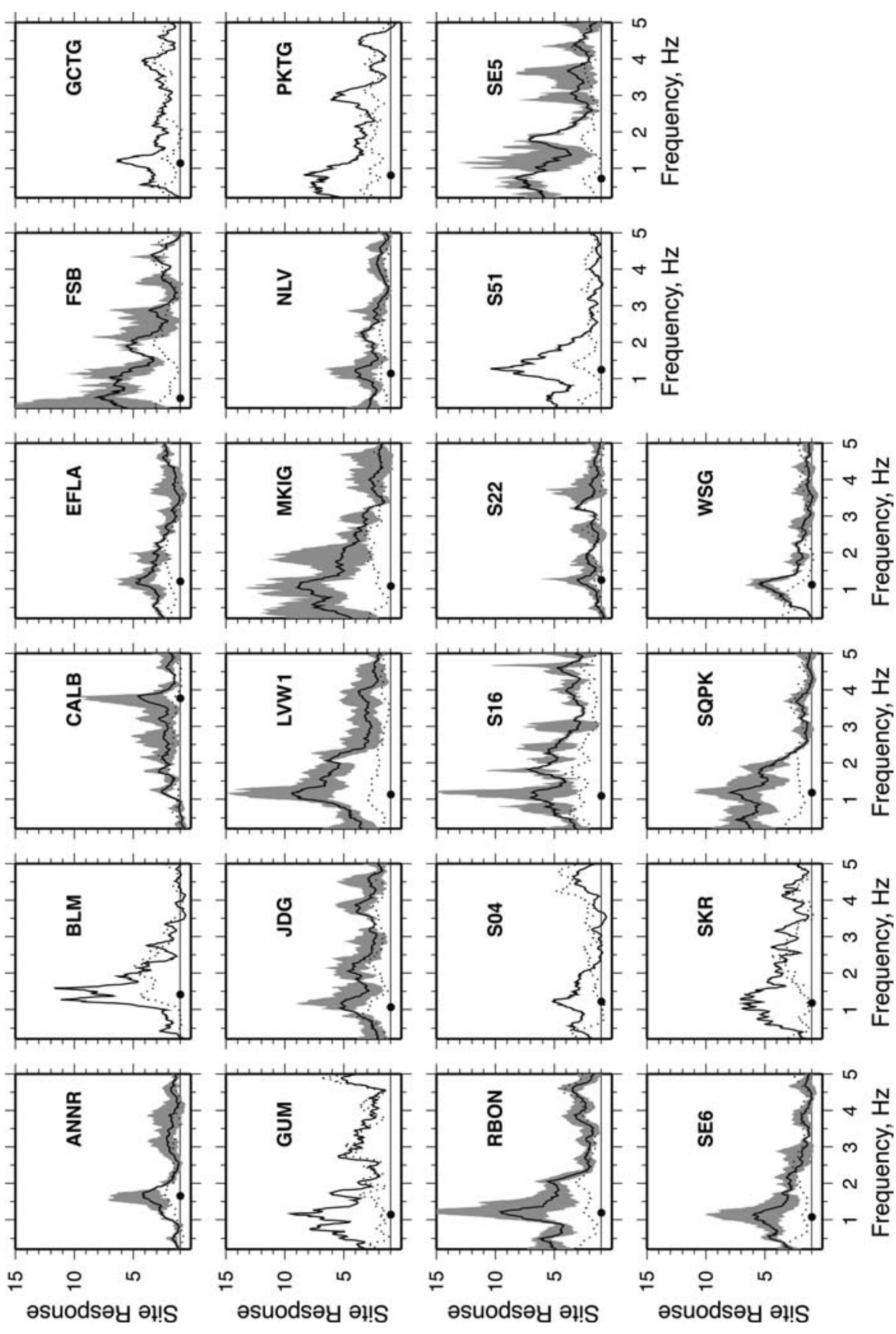

Figure 4

Site response estimates (log-average) at the BLUME-NTS sites from the SSR method (black lines) with uncertainties (grey, 2 standard deviations of the mean) and HVR method (dotted lines). The frequency of peak SSR response is indicated by the black circle.

and uncertainties were computed using the standard deviation of the log-averaged mean (FIELD and JACOB, 1995).

We also computed Horizontal-Vertical Spectral Ratio (HVR; LERMO and CHAVEZ-GARCIA, 1993) using the S-wave spectral amplitudes as described above. The root-mean-square vector averaged horizontal component spectra were divided by the vertical component spectrum to form the HVR. Because this method does not require observations at the reference site, we were able to use as many as thirteen nuclear explosions at 23 BLUME-NTS sites.

Site Response Results

Site response measurements for the BLUME-NTS, BLUME-LSM and LVVBB data sets are presented in Figures 4, 5 and 6, respectively. Site response from the SSR method at the BLUME-NTS sites includes uncertainties whenever possible (Fig. 4). Many stations have peak SSR site response in the range 0.5–2 Hz and are quite large, approaching a factor of ten. Uncertainties for the BLUME-NTS log-averaged site response estimates are typically large at the peak response near 1 Hz due to variability in the individual curves. Site response curves from the HVR method often show peaks at the same frequencies as the SSR curves but the amplification is typically less than the SSR curve. This is consistent with previous reports (FIELD and JACOB, 1995; LACHET *et al.*, 1996; BONILLA *et al.*, 1997; RIEPL *et al.*, 1998). Our results generally show good agreement between the SSR and HVR amplifications for frequencies above about 2 Hz.

Many BLUME-NTS sites show a peak near 1 Hz, while the BLUME-LSM sites show multiple peaks. The lowest frequency peak is identified in the site response estimates shown in Figures 4 and 5 for the BLUME-NTS and BLUME-LSM data, respectively. The LVVBB sites in the northern part of the basin, specifically CHY, F02, F04, F20 and VAH reveal multiple peaks (Fig. 6) similar to the BLUME-LSM sites ST10 and ST16 (Fig. 5). Where possible, we compared site response curves from the SSR method using different data sets. Figure 7 presents the SSR curves for five sites in common between data sets. The agreement is generally good, but some discrepancies are seen for large amplitude peaks at ST16-F04 and SQPK-SQP. One of the challenges of this study is the integration of site response measurements from different data sets without specific details on the historical site installations. The BLUME-NTS and BLUME-LSM sites were installed in locations that have changed dramatically due to rapid urbanization of LVV. This is especially acute for the SGS/ST17 site near Grant Stewart Reservoir in a relatively new housing development on the flank of Frenchman Mountain. We expect that some of the discrepancies seen at sites shown in Figure 7 are due to different behavior at the BLUME and LVVBB site SGS. We return to this issue later.

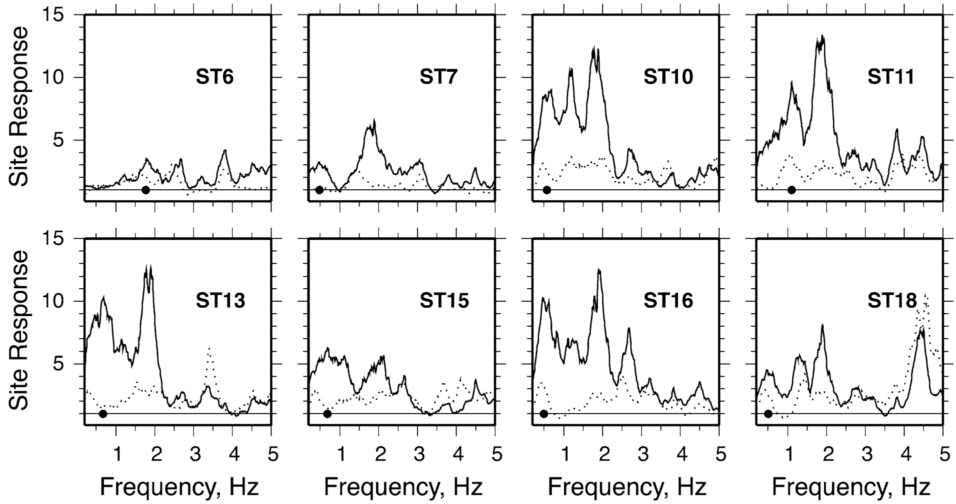

Figure 5
Site response estimates at the BLUME-LSM sites from the SSR method (black lines) and HVR method (dotted lines). The lowest frequency of peak SSR response is indicated by the black circle.

To illustrate the spatial variability in site response across LVV, we demonstrate band-averaged SSR measurements at each site plotted in map view in Figure 8. Site response is lower on the Valley's west side where the basin depth is less than 1 km. Larger amplifications for frequencies below 2.0 Hz are observed in the central and northern sections of LVV where the basin depth exceeds 1 km. These maps suggest a correlation with basin depth based on the model of LANGENHEIM *et al.* (2001a) presented in Figure 2a. Site response in the same frequency bands is plotted versus the basin depth in Figure 9. The depth-to-basin was computed as the average depth in a 1 km square beneath each site (LANGENHEIM *et al.*, 2001a). This figure shows a striking correlation between site response and basin depth, especially for frequencies between 0.2 and about 2.0 Hz. The BLUME-NTS sites cover the central and southern portion of LVV where the basin depth is generally less than 3 km. BLUME-LSM and LVVBB sites contribute information on the northern, deeper part of LVV. The BLUME-NTS data are consistent with the BLUME-LSM data in these linear trends. However, the LVVBB data reveal lower amplifications versus basin depth, especially in the band 0.8–3.0 Hz. This may be due to amplification at the LVVBB SGS site relative to the BLUME-NTS SGS site. Linear regression fits of band-averaged site response versus basin depth are shown in each plot. We computed regressions for all three data sets together and the BLUME-NTS and BLUME-LSM data together. The BLUME-NTS and BLUME-LSM data manifest a stronger correlation versus basin depth than the combined data set, regardless of the choice of reference site (SGS/ST17 or CALB/ST06).

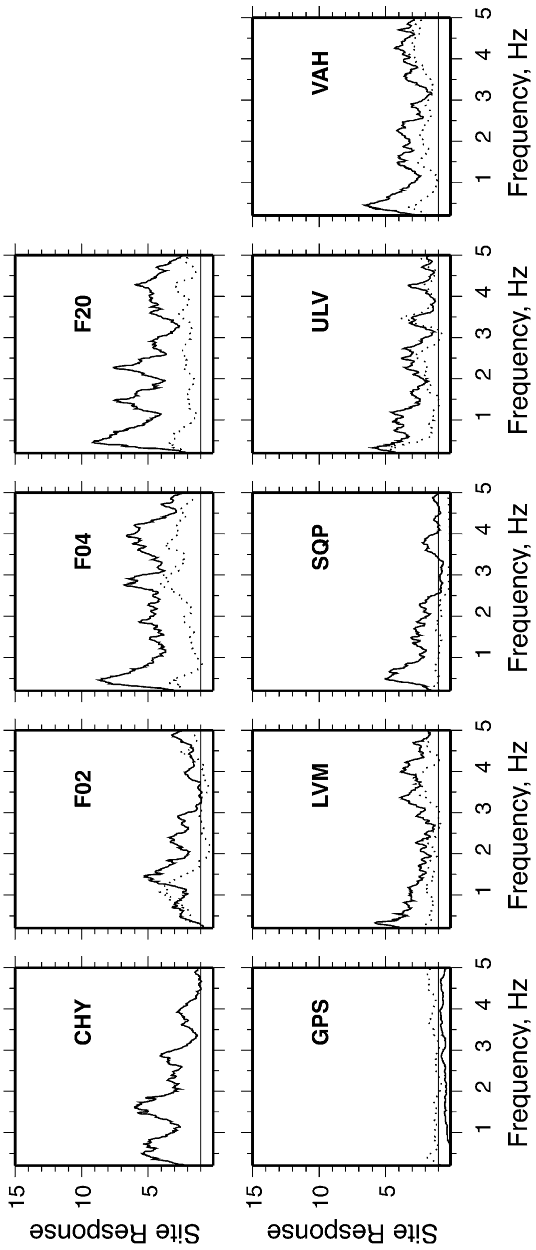

Figure 6
Site response estimates at the LVVBB sites from the SSR method (black lines) and HVR method (dotted lines).

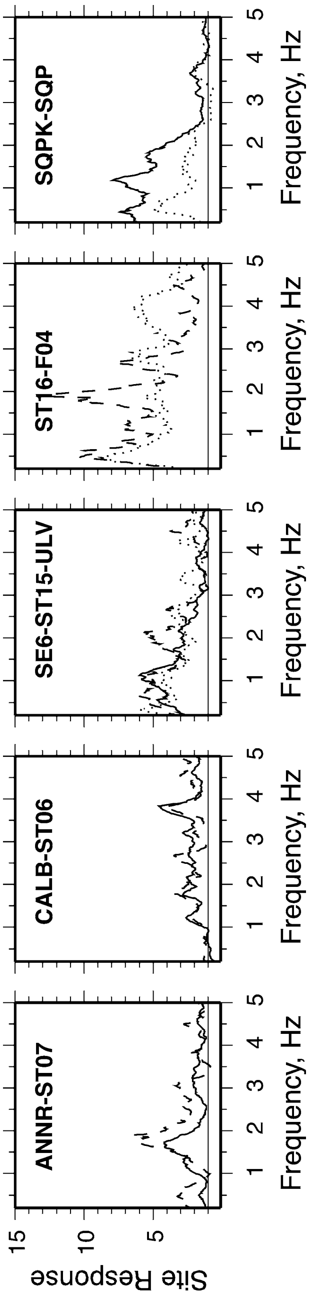

Figure 7
Comparison of SSR site response curves for sites in common to the BLUME-NTS (solid), BLUME-LSM (dashed) and LVVBB (dotted) data sets.

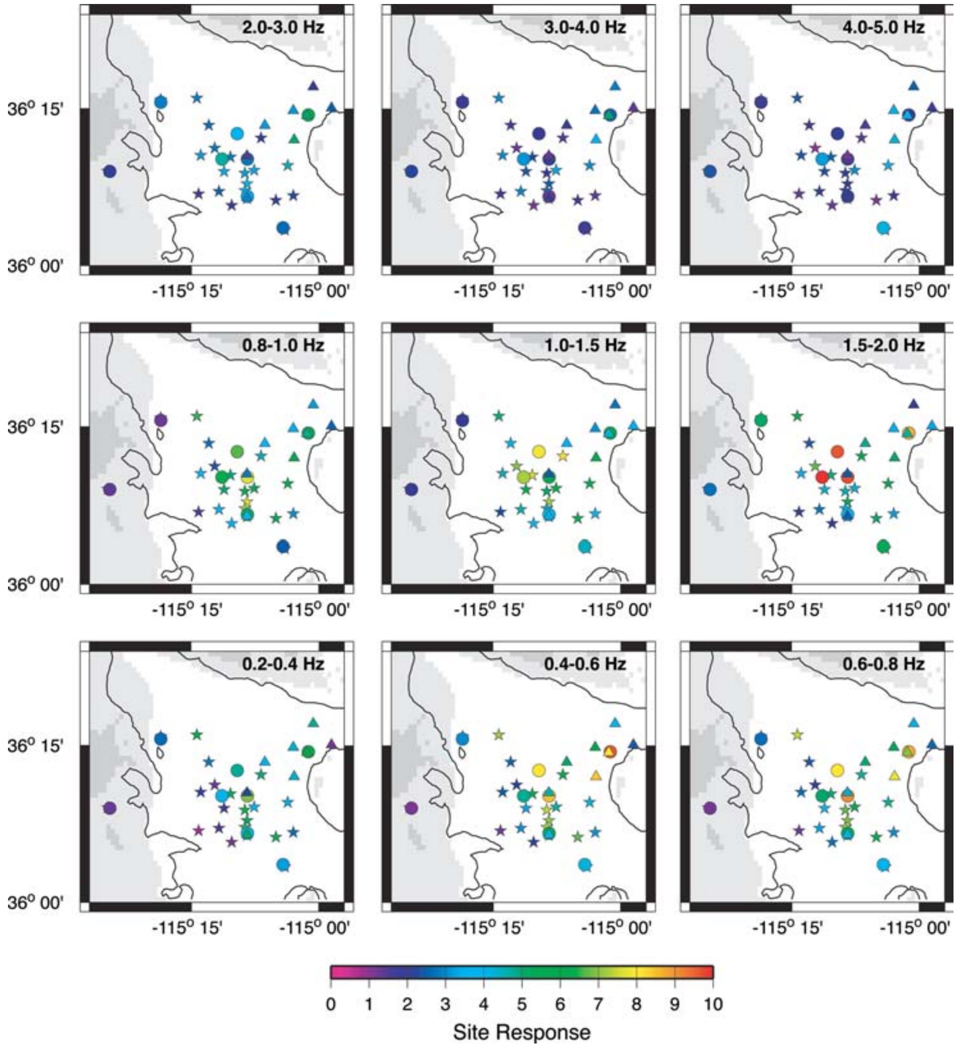

Figure 8
Map of band-averaged SSR site response estimates in LVV from the BLUME-NTS (stars), BLUME-LSM (circles) and LVVBB (triangles) data sets. In each map the basin contact from LANGENHEIM *et al.* (2001a) is shown (black lines).

Considering the standing wave explanation of the fundamental mode resonance of a layer over a half-space, the relationship between the resonant frequency, f_0, is $f_0 = \beta/4h$, where β is the shear-wave velocity and h is the thickness (KRAMER, 1996). For the entire sedimentary column (up to 4 km) to contribute to the observed site response peaks, the shear velocities would have to take unrealistically high values. To explore the possible dependence of site response with basin depth, we plotted the

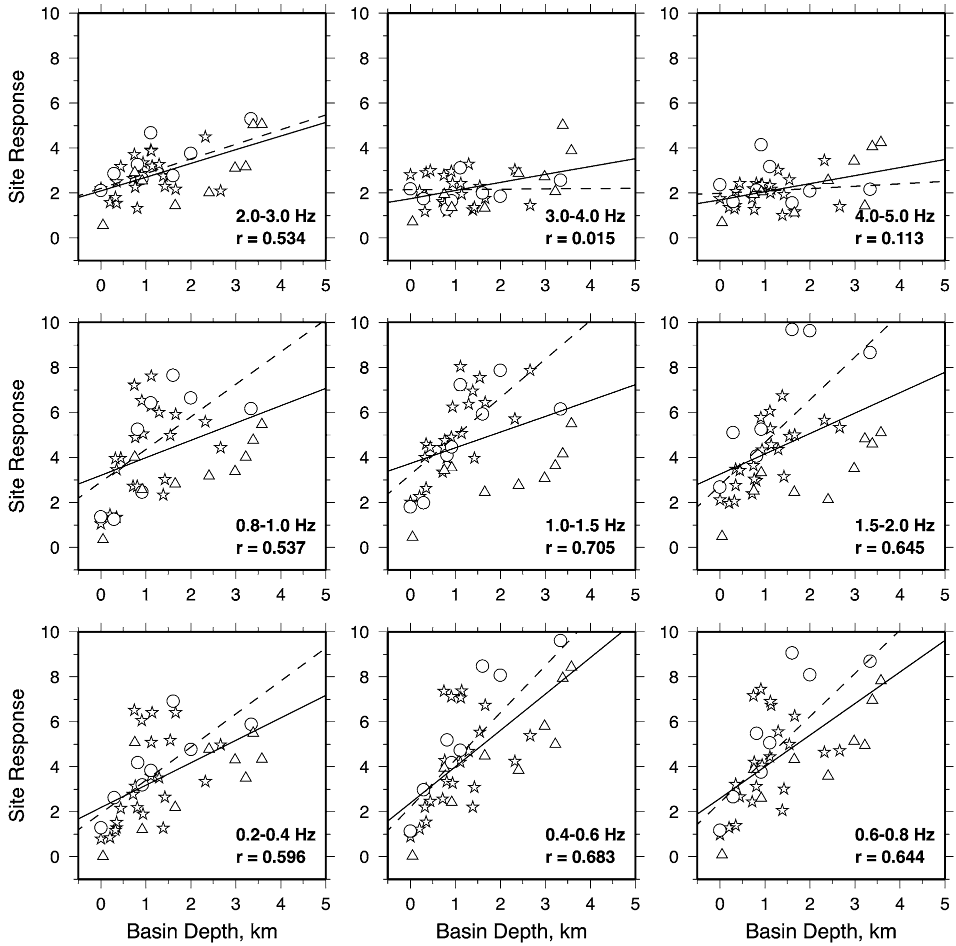

Figure 9
Band-averaged SSR site response estimates in LVV versus basin depth from the model of LANGENHEIM *et al.* (2001b) for the BLUME-NTS (stars), BLUME-LSM (circles) and LVVBB (triangles) data sets. Linear regression fits for all three data sets (solid line) and the combined BLUME-NTS and BLUME-LSM data sets (dashed) are shown. The linear correlation, *r*, of the joint BLUME-NTS and BLUME-LSM data set is given in each panel.

frequencies of peak SSR site response versus basin depth and in map view (Fig. 10). Note that the frequencies of peak response cluster near frequencies 0.6, 1.2 and 2.0 Hz do not show a trend with basin depth. In fact sites with very different basin depths have similar peak frequencies (e.g., S22, NLV, SE6, SQPK, S51, Fig. 4). For the peak amplifications to be related to a one-dimensional layer over a half-space model, the frequencies should scale as 1:3:5, instead of the observed 1:2:~4. This point further detracts from the simple one-dimensional layer over a half-space model.

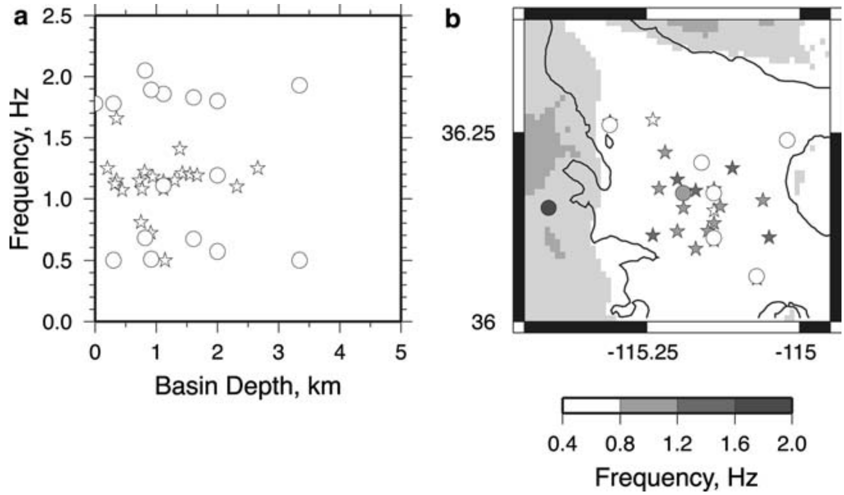

Figure 10
(a) Frequencies of peak response at BLUME-NTS and BLUME-LSM sites versus basin depth. (b) Map of lowest frequency of peak response at BLUME-NTS and BLUME-LSM sites projected at site location.

The correlation of site-specific amplification with basin depth (Fig. 9) does not prove a causal relationship, but simply provides a convenient and suggestive way to display the data. The deeper sections of the basin are likely to have higher velocity consolidated sediments at depth (TABOR, 1982; SNELSON *et al.*, 2003) that have little influence on amplification. It is possible that basin depth is correlated with low-velocity near-surface sediments due to transport of recent alluvial fill to lower elevations in the northern, deeper basin. It is well known that low shallow shear-wave velocities are likely to result in higher site response (e.g., ANDERSON *et al.*, 1996; BOORE and JOYNER, 1997; HARMSEN, 1997; FIELD *et al.*, 2000; MARTIROSYAN *et al.*, 2002). We compared site response curves at locations where we have preliminary geotechnical shear-velocity results (LUKE *et al.*, 2002; LIU *et al.*, 2004). We represented each profile by the average shear-wave velocity for the upper 30 meters (V_{30}). These indeed show that the large amplification at LVW1 occurs with the lowest V_{30} and the sites with lower amplification have higher V_{30} (Fig. 11). In the following section, we attempt to understand the observed site response with a series of modeling experiments.

Two-dimensional Elastic Finite Difference Modeling

In an attempt to better understand the structure controlling site response in Las Vegas we performed a series of two-dimensional (2-D) finite difference calculations. Three-dimensional (3-D) elastic finite difference simulations (e.g., GRAVES, 1996)

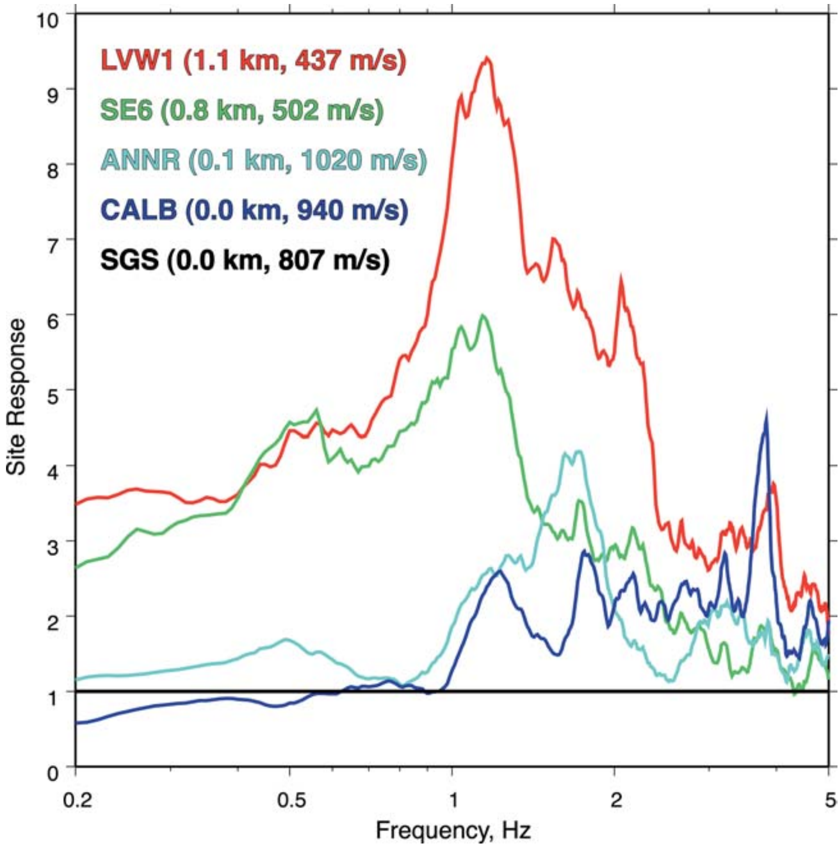

Figure 11
Site response curves for BLUME-NTS sites LVW1, SE6, ANNR, CALB and SGS. The basin depth and preliminary V_{30} at each site are shown.

have been used to understand and predict ground motions for past and scenario earthquakes (OLSEN *et al.*, 1995; STIDHAM *et al.*, 1999; OLSEN, 2000). Low near-surface velocities in sedimentary basins require close grid spacing in order to satisfy numerical accuracy conditions for finite difference solutions. The simulation of ground motion response up to 1 Hz in 3-D for ranges typical of the NTS-LVV paths (~130 km) requires high performance parallel computing resources (LARSEN, 2002). We instead chose to perform a series of 2-D simulations on a desktop computer that allowed us to investigate a range of models and experiment with various features of the models. 2-D simulations cannot correctly represent spherical geometric spreading and out-of-plane propagation effects. However, since the goal of our modeling is to reproduce the low-frequency amplification of basin sites relative to a hard-rock reference site, 2-D modeling is adequate. We used the LLNL-developed *E3D* 4th order staggered grid finite difference code (LARSEN and SCHULTZ, 1995). These calculations were performed for a 233 km by 75 km Cartesian box with 0.05 km (50 m) grid spacing. Accurate calculations were possible for frequencies up to 1.5 Hz.

We used a cross section from the LSM epicenter to LVV through the LANGENHEIM *et al.* (2001a) basin model to determine the depth to basement (Fig. 12). We fixed the velocity profile through the crystalline crust and mantle, but allowed the velocity profile in the basin to vary with special emphasis on the shallowest velocities (< 250 m). The crustal model is based on PATTON and TAYLOR (1984), but we increased the surface velocities to be consistent with hard rock lithologies (NEHRP A classification) at the surface (Table 2). A double-couple source for the Little Skull Mountain earthquake at approximately 100 km from the basin provided the excitation. The horizontal and vertical component ground velocities were sampled at regular intervals within and adjacent to the basin. We then computed the horizontal component SSR between the basin sites and the reference site. To illustrate the effects of low-velocity sediments, Figure 12a compares the response of a 1-D crystalline crustal model (solid grey lines) and a 2-D model with the sedimentary basin (dashed lines). Note the higher amplitudes and longer duration of the sedimentary response. However, the reference site adjacent to the basin has a similar, lower amplitude response for both models.

Figure 13 reveals observed site response at two sites with high amplification, ST10 and RBON. The ST10 site response curve shows the larger peak near 0.6 Hz and both curves show the peak response near 1.2 Hz. Recall that many sites show the peak near 1.2 Hz (Fig. 10). Figure 13 also depicts the synthetic site response and corresponding sedimentary models investigated in the numerical experiments. We chose a range of models including discretized linear gradients ("stair step" models), layered models and low shallow velocities. Figure 13a illustrates the site response resulting from discretized linear gradient models with greatly different average velocities. These models result in a peak at relatively low frequencies (~0.3 Hz) and another in the range 1.0–1.4 Hz. One model in particular results in a peak near 1.2 Hz similar to the observations. However, all the models predict a large low-frequency response at about 0.3 Hz. Models with a linear gradient in the sedimentary section and a discontinuous near-surface low velocity layer result in lower amplitude peaks near 0.3 Hz and 1.0 Hz (Fig. 13b). A uniform basin model with near-surface low velocities is considered in Figure 13b, but fails to produce peaks seen in the observed site response curves. Using estimates of sedimentary velocities from preliminary seismic refraction analysis (SNELSON *et al.*, 2003), we investigated models with four layers and varied the near-surface velocities (Figs. 13c and 13d). Some of these models result in large amplitude peaks near 0.4 and 1.0 Hz (Fig. 13c). Two models produce peaks of similar amplitude and frequency as observed (Fig. 13d). These models have low velocity shallow layers: 600 m/s and 200 m thick producing a peak at 0.6 Hz and 750 m/s and 100 m thick producing a peak at 1.2 Hz. While the models shown in Figure 13d do not match both peaks near 0.6 and 1.2 Hz, they certainly illustrate that the near-surface low velocities strongly impact site response

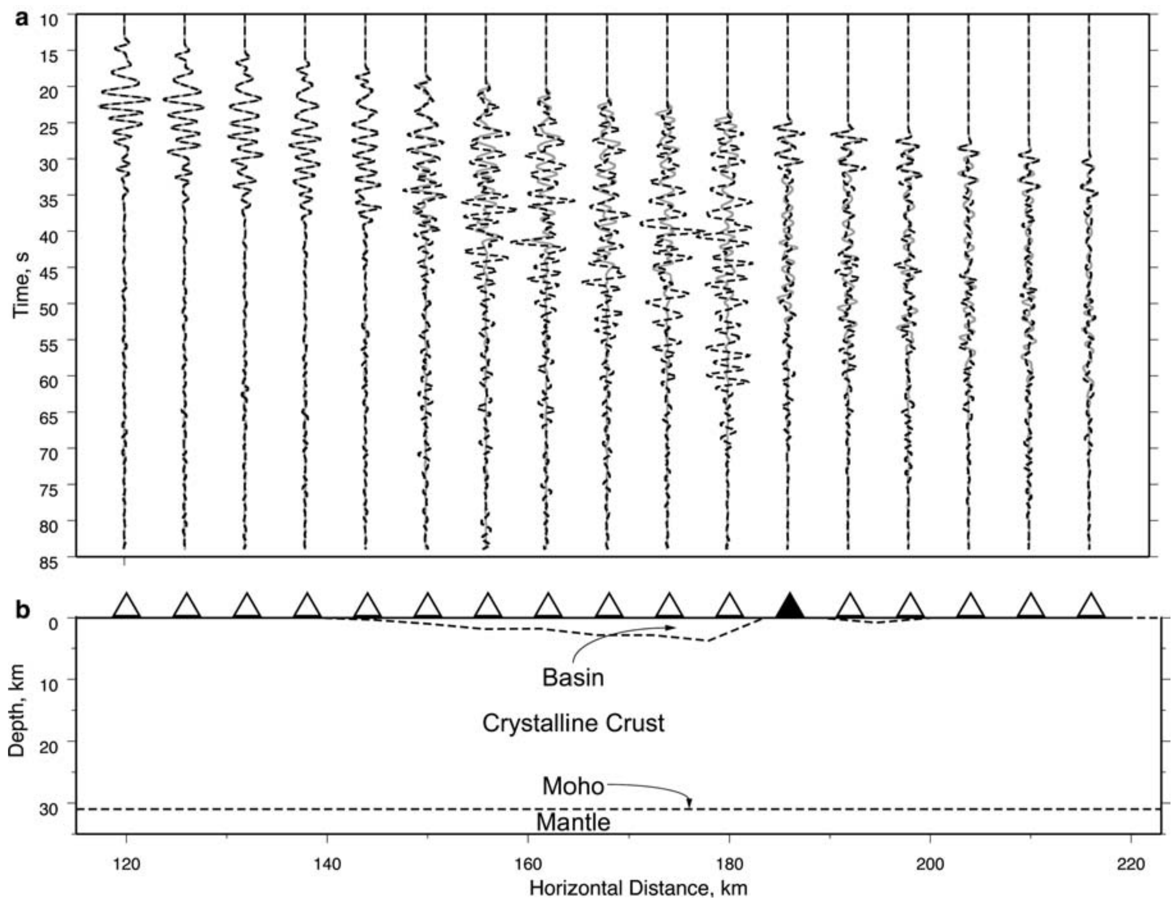

Figure 12

(a) Theoretical seismograms from elastic finite difference modeling showing the response from the 1-D crustal model without the basin (solid) and the response with the low velocity sediments in the basin (dashed). (b) The wavefield is sampled at the sites indicated by the triangles. Theoretical site response is computed using the reference site (black triangle). The basin profile through Las Vegas Valley is taken from the LANGENHEIM *et al.* (2001a,b) model.

Table 2

"Hard rock" velocity model for finite difference simulations based on PATTON AND TAYLOR *(1984)*

Depth (km)	Thickness (km)	V_P (km/s)	V_S (km/s)	ρ (kg/m^3)	Q_P	Q_S
0.0	1.00	3.210	1.900	2330	190	85
5.80	4.8	5.930	3.500	2770	190	85
10.0	4.2	5.950	3.510	2770	190	85
12.0	2.0	5.970	3.520	2780	386	172
15.0	3.0	6.000	3.540	2780	386	172
18.0	3.0	6.070	3.580	2790	386	172
21.0	3.0	6.200	3.660	2810	386	172
24.0	3.0	6.310	3.720	2830	233	103
27.0	3.0	6.360	3.750	2840	233	103
31.0	4.0	6.410	3.778	2850	233	10
61.0	30.0	7.900	4.400	3200	112	50
101.0	40.0	7.900	3.300	3300	72	31
117.0	16.0	7.900	4.100	4120	210	93
137.0	20.0	7.900	4.050	3400	240	107

and specific combinations of layer thickness and velocity can predict features in the site response observations.

Conclusions and Discussion

In this article, we combined different data sources to estimate site response across a wide area of Las Vegas Valley (LVV). Our measurements greatly expand the coverage of LVV over previous studies. Site amplification is variable, with site-averaged amplifications approaching a factor of ten. However the frequencies of peak site response are relatively stable and low frequency (0.5–2.0 Hz). These results confirm and extend the conclusions of MURPHY and HEWLETT (1975) and SU *et al.* (1998) that low-frequency amplification exposes Las Vegas to ground motion hazard from distant earthquakes. Low frequency ground motions from distant earthquakes can affect large structures such as tall buildings and hotels in Las Vegas. Our extensive site response results can be used in seismic hazard assessment, to scale observed ground motions and/or predict ground motion from possible scenario earthquakes.

The correlation of amplification with basin depth is intriguing. The fact that the frequencies of peak site response are relatively stable across LVV suggests that basin depth is not the only controlling factor for the large amplitude low frequency (< 1.5 Hz) site response peaks. A standing wave explanation of a layer over a half-space cannot explain the peak amplification frequencies. Our modeling experiments indicate the shallow velocities can predict the site response peaks observed at many sites: 600 m/s in a 200 m layer can reproduce the 0.6 Hz and 750 m/s in a 100 m

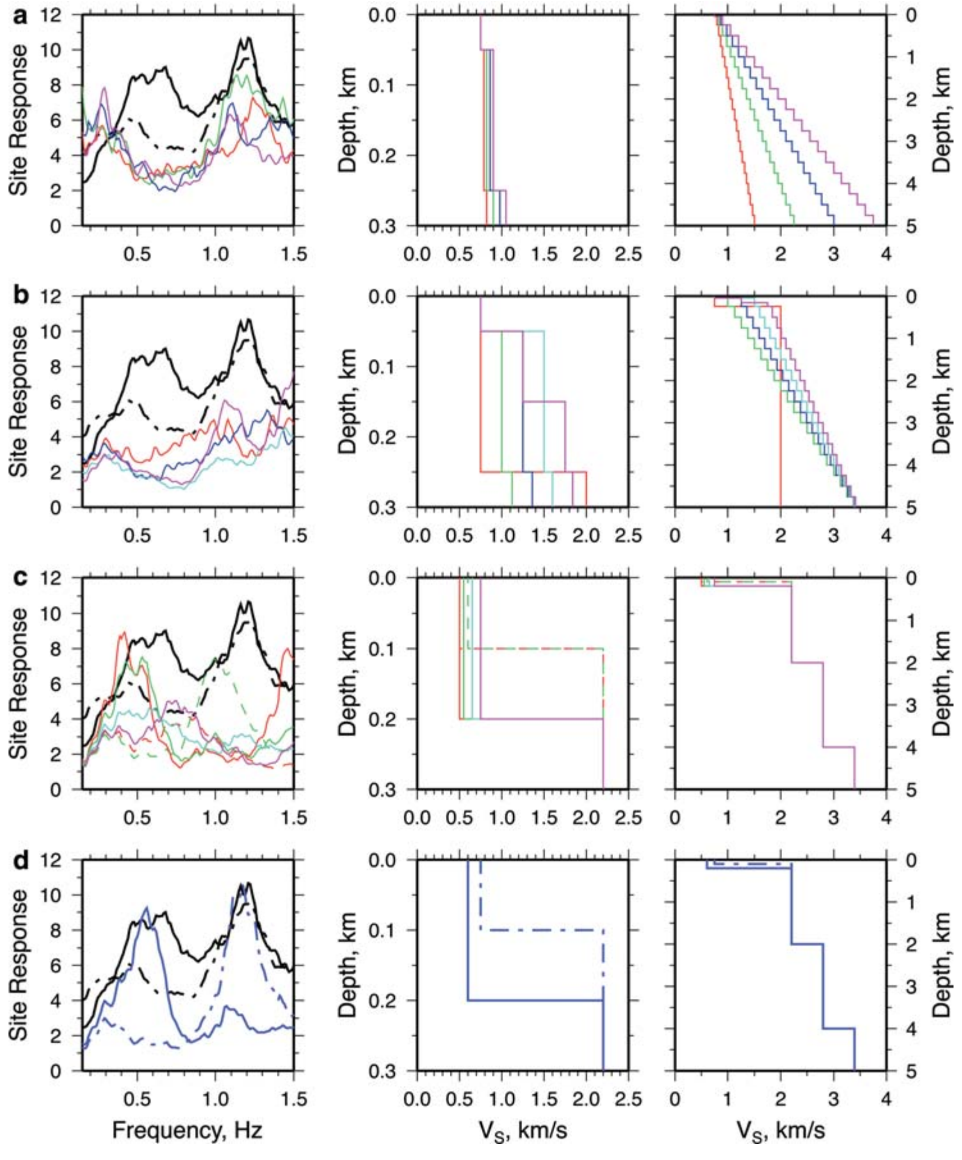

Figure 13
Observed SSR site response at ST10 (solid black) and RBON (black dashed) and simulations (left panels). Sedimentary velocity models are shown for the shallow (center panels) and deep (right panels) sections: (a) linear gradient models, (b) linear gradient models with a near-surface velocity jump; (c) layered models with low near-surface velocities in the upper 100 m (750 m/s) or 200 m (600 m/s); and (d) best-fitting layered models with velocity jumps at 100 and 200 m. Theoretical site response curves (left) are color-coded to the velocity models (center and right).

thick layer reproduces the peak at 1.2 Hz. These results are certainly not unique, e.g. other models can probably fit the data equally well. However, the modeling results clearly preclude models with high near-surface shear velocities or gradual velocity gradients, such as those in Figures 13a and 13b.

The basin-fill materials that are most likely to influence site amplification lie in the geotechnical layer over the deeper parts of the basin. Comparison of site response amplification with slowness-averaged geotechincal velocities to 30 meters (V_{30}) indicate that low near-surface velocities control amplification, similar to previous studies (e.g., ANDERSON *et al.*, 1996; BOORE and JOYNER, 1997; HARMSEN, 1997; FIELD *et al.*, 2000; MARTIROSYAN *et al.*, 2002). The deepest portions of the basin are likely to contain higher velocity (SNELSON *et al.*, 2003), consolidated Miocene-age sediments (TABOR, 1982; BOHANNON, 1984) that have limited influence on amplification. It is possible that basin depth is correlated with low-velocity near-surface sediments due to the formation of paleo-lakes or streams in the deeper basin. A preliminary investigation of shallow lithology indicates that low-velocity clay-rich sediments, that are likely to enhance amplification, fill the basin from a few hundred meters to near-surface depths (Wanda Taylor and Jeffrey Wagoner, personal communication).

While our 2-D finite difference modeling can capture most of the important physics of wave propagation in the basin, other factors are clearly important, such as topography and lateral velocity variations within the basin and surrounding crust. The subsurface is likely to be composed of lenses of different materials with different velocities and densities. Our modeling did not address the effects of such structures. It is also likely that larger scale three-dimensional effects also play a role in the observed site response (e.g., OLSEN, 2000; LARSEN, 2002). As more detailed models of structure in and around LVV emerge, including fine structure near the surface, resource demanding high-performance computations will result in a better understanding of the observed site response.

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