Nevada Bureau of Mines and Geology Special Publication 36

Ground Motions from the 2008 Wells, Nevada Earthquake Sequence and Implications for Seismic Hazard

by

Mark Petersen[1], Kris Pankow [2], Glenn Biasi[3], Mark Meremonte[1], Stephen Harmsen[1], Charles Mueller[1], and Yuehua Zeng[1]
[1] U. S. Geological Survey, Golden, CO
[2] University of Utah, Salt Lake City, UT
[3] University of Nevada, Reno

2011

ABSTRACT

We analyze aftershock and mainshock ground motion recordings of the M_W 6.0 Wells, Nevada earthquake of February 21, 2008 and use these data to examine the seismic hazard in the region. This mainshock occurred on an unmapped fault in a region characterized by moderately low rates of seismicity, geodetic strain, and slip on mapped faults. Ground motions from the Wells earthquake are similar to values given by ground motion prediction equations but decay faster at distances greater than 200 km. An aftershock of M 4.7, that occurred the day after the mainshock, caused lower ground motion than expected from current ground motion prediction equations. However, strong ground motions recorded at the Wells Fire Station were higher than calculated by using the ground motion models. We analyze this station's strong motion record by modeling the Fourier amplitude spectra for source and site effects. This analysis indicates that the aftershock may have had higher than average stress drop and that soil amplification is most likely an important factor. The mainshock ground motions were also recorded by seismic stations in the Salt Lake City region. These recorded ground motions appear to have been amplified by sedimentary basin effects. We make specific recommendations on how to improve ground motion estimates for future earthquake hazard assessments in this region.

INTRODUCTION

The February 21, 2008 Wells, Nevada earthquake (M_W 6.0 USGS; http://earthquake.usgs.gov/) was located 9 km northeast of the town of Wells and was felt throughout eastern Nevada, southern Idaho, and western Utah. This normal-faulting earthquake caused significant damage to unreinforced masonry buildings and infrastructure (dePolo, this volume) and is, therefore, an important consideration in developing future seismic hazard and engineering design maps for the Intermountain West region.

The Wells mainshock ruptured along a previously unmapped fault that strikes to the northeast and dips 55 degrees to the southeast (Smith and others, this volume), similar to other nearby structures in the Basin and Range Province. Aftershocks delineate the normal mainshock rupture source as well as some subsidiary faults to the north with strike-slip mechanisms (Bob Herrmann, 2008). Several faults have been identified near Wells, but paleoseismic studies indicate a low rate of seismic activity during the Holocene (Petersen and others, 2008). Most of these faults have measured long-term slip rates of a few millimeters per year and recurrence times of large earthquake ruptures on the order of a few thousands of years. Following the event geologists searched for evidence of tectonic ground ruptures, but none were identified in the region surrounding the earthquake (dePolo, this volume).

The mainshock ground motions were well-recorded by about 50 regional stations of the Advanced National Seismic System (ANSS) and EARTHSCOPE stations at distances from 40 km to 350 km from the rupture. Seismological studies using these data indicate that modeled slip during the mainshock rupture was concentrated on a compact 6.5 km by 4 km region located updip from the hypocenter, having a stress drop of about 72 bars and a moment of 6.2 X 10^{24} dyne-cm

(Mendoza and Hartzell, 2009). This stress drop is higher than the median stress drop for global normal-fault mechanisms which Allmann and Shearer (2009) calculate as ranging from 20 to 30 bars.

Seismic hazard analysis requires estimates of strong-ground motions at distances less than 40 km where the majority of the damage occurs. Therefore, we also deployed a temporary seismic network about a day after the mainshock in a cooperative effort by the University of Utah, University of Nevada, and U. S. Geological Survey (USGS). These aftershock records help define the earthquake rupture properties and provide evidence of local site modifications to the strong ground shaking. These local and regional ground motion data are important for updating the ground motion prediction equations (GMPEs) that are used in the hazard maps.

In this paper we discuss the National Seismic Hazard Maps in light of the 2008 Wells earthquake. We examine the properties of this event to make recommendations about source models in the Intermountain West region. By comparing ground motions from the Wells mainshock and aftershocks with ground motion prediction equations (GMPEs) and aftershock spectra we can update the ground motion models to improve the seismic hazard maps.

SEISMIC HAZARD NEAR WELLS, NV

The Wells, NV earthquake occurred in a region that has not experienced significant seismic activity during the past 75 years; only 7 M $\geq$ 4.0 earthquakes are included in the USGS earthquake catalog within 100 km of Wells during this period (figure 1). Historic seismicity, geologic slip rate and geodetic strain rate studies are used to estimate the recurrence intervals of earthquakes in regions such as Wells. Generally, slower strain rates on a fault or across a region suggest longer earthquake recurrence intervals and lower seismic hazard. The GPS-based strain rate data near Wells provide evidence for strain accumulation rates that are a factor of 10 to 30 lower than strain rates observed near the California plate boundary (figure 2; Petersen and others, 2008). Geologic slip rates on extensional faults near Wells are consistent with M ~ 6 earthquakes occurring every few hundreds of years and M ~ 7 earthquakes every few thousands of years (Petersen and others, 2008).

The 2008 USGS National Seismic Hazard Maps (NSHMs) were revised in 2006-2007 and indicate moderate to low hazard based on the low observed seismic activity over the past 75 years, low geodetic strain rates, and geologic evidence of long recurrence intervals on the faults that bound the extensional horsts and grabens of the Basin and Range province. They were revised from the 2002 version by applying new fault parameters (e.g., dip of faults), an updated earthquake catalog, and new ground motion prediction equations (GMPE; Petersen and others, 2008). These hazard maps are based on ground motions at a 2% probability of exceedance in 50 years level, the hazard level considered in current engineering design codes.

The hazard maps were developed by combining contributions from random background earthquakes, based on the earthquake catalog of M $\geq$ 4.0 earthquakes, and earthquake ruptures on active faults, based on studies of prehistoric earthquakes on Quaternary faults. A background seismic source model is applied because it is recognized that earthquakes like the Wells event occur periodically and are important to the seismic hazard. Random magnitude 5.0 to 7.0 earthquakes with rates determined by historical seismicity were included in this model to account for earthquakes on unknown faults and moderate size earthquakes on known faults. Earthquakes on faults are modeled using slip rate information to assess recurrence and fault length information to assess earthquake magnitude. Ground motions were calculated for each source in the model using three Next Generation Attenuation (NGA) GMPEs that relate peak ground acceleration and spectral acceleration ground motion distributions to the earthquake magnitude, distance, fault type, soil class, hanging-wall and foot-wall terms, depth of rupture, and other factors. Hazard was calculated for both normal and strike-slip earthquakes, because the NGA GMPEs distinguish between these two classes of earthquakes. Normal faults included in the source model have dips that range from 40-60 degrees with 50 degrees considered the most likely. Seismic hazard maps and related input data can be found at http://earthquake.usgs.gov/hazmaps/.

The seismic hazard map for peak horizontal ground acceleration (PGA) with a 2% probability of exceedance in 50 year hazard level is shown in figure 1 for a uniform alluvial soil condition, defined as having a shear wave velocity in the upper 30 m of 259 m/s (NSHRP soil class D). The map indicates a peak horizontal acceleration (PGA) hazard that ranges from about 0.2 to 0.3 g for the region closest to Wells, NV(figure 1). The relative contributions to the hazard at Wells, NV from all the earthquakes included in the model are shown in the hazard deaggregation plot (figure 3). Most of the hazard at Wells is contributed by M 6.0-7.1 events at distances less than 15 km. Large earthquakes on the Ruby Mountain fault, located just to the southwest of Wells (figure 1), contribute 50% of the hazard. This fault is, characterized with a long-term average net slip rate of 0.28 mm/yr and ruptures of large earthquakes with M 6.9 to 7.1 that recur every few thousands of years (see Petersen and others, 2008). Random background sources account for the other 50% of the hazard at Wells, NV. Earthquakes like the 2008 Wells M 6.0 earthquake are accounted for by this random background earthquake component of the probabilistic hazard model. The time-independent probability of a M 6 or greater earthquake within 50 km of Wells is about 3-5% in a 30 year interval (figure 4). The probabilities we calculate are similar to the rates implied by the Anderson model (2010, this volume).

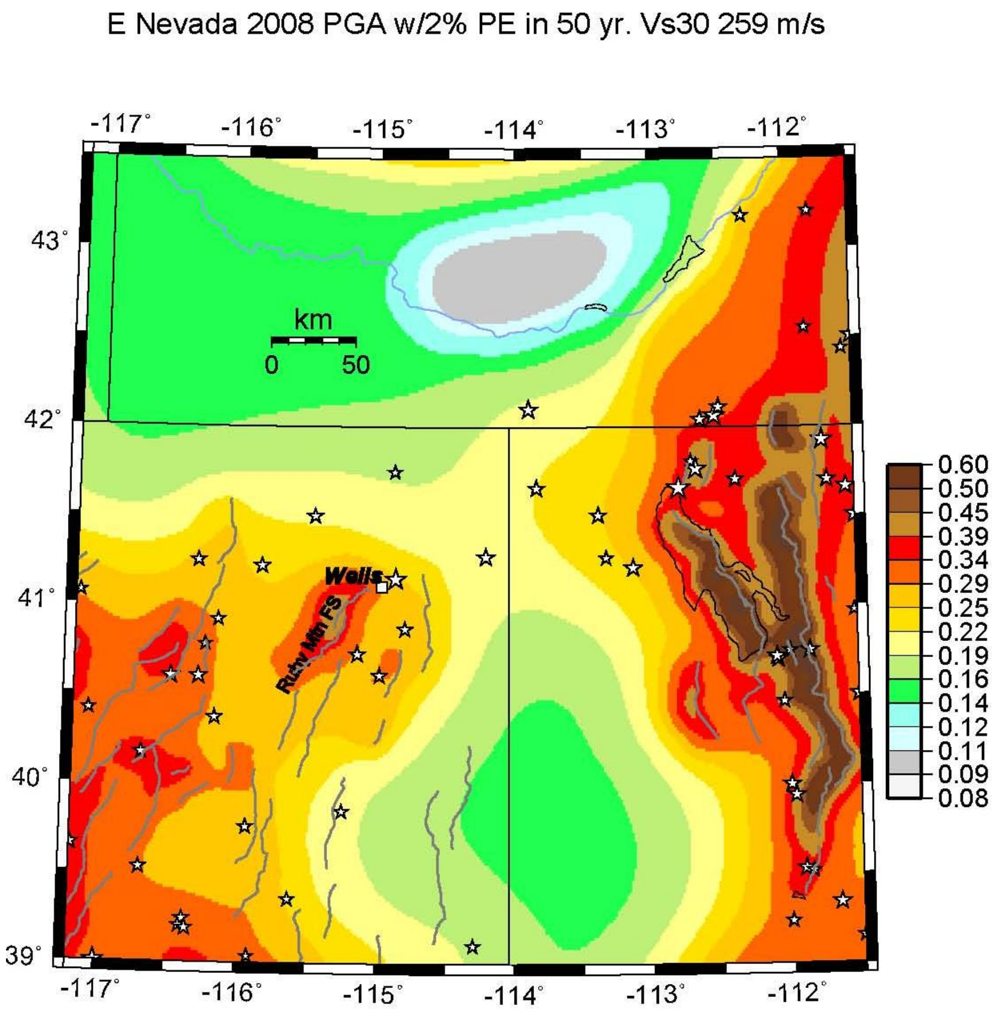

Figure 1. 2008 USGS NSHM of Wells, Nevada and vicinity for peak ground acceleration at 2% probability of exceedance in 50 years on uniform D soil class (Petersen and others, 2008). Data basis for the 2008 NSHM did not include the Wells earthquake. Stars represent historical earthquakes with M ≥ 4.

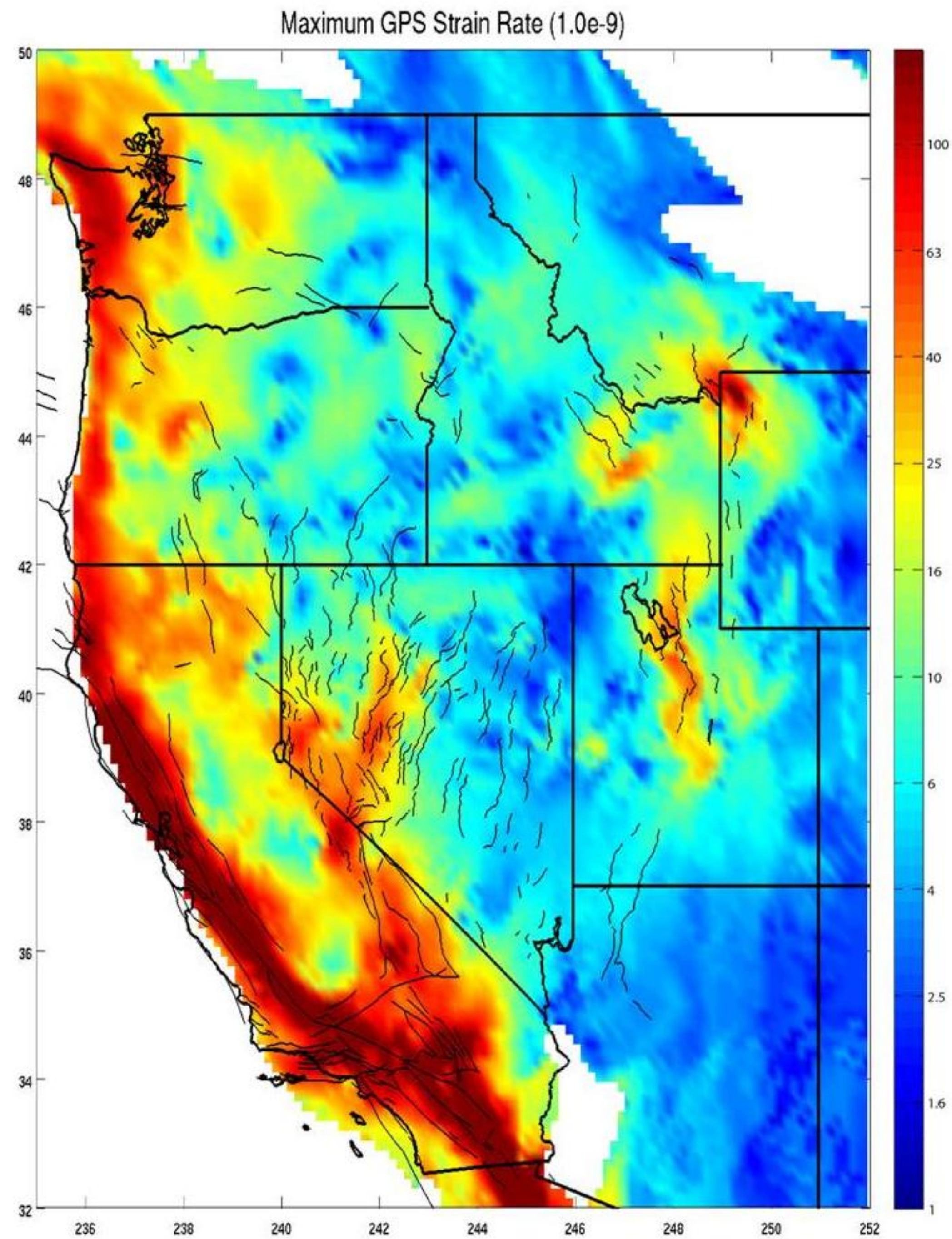

Figure 2. Maximum geodetic strain rate per year across the western U.S. (Petersen and others, 2008). Wells, NV is located in the northeast corner of Nevada.

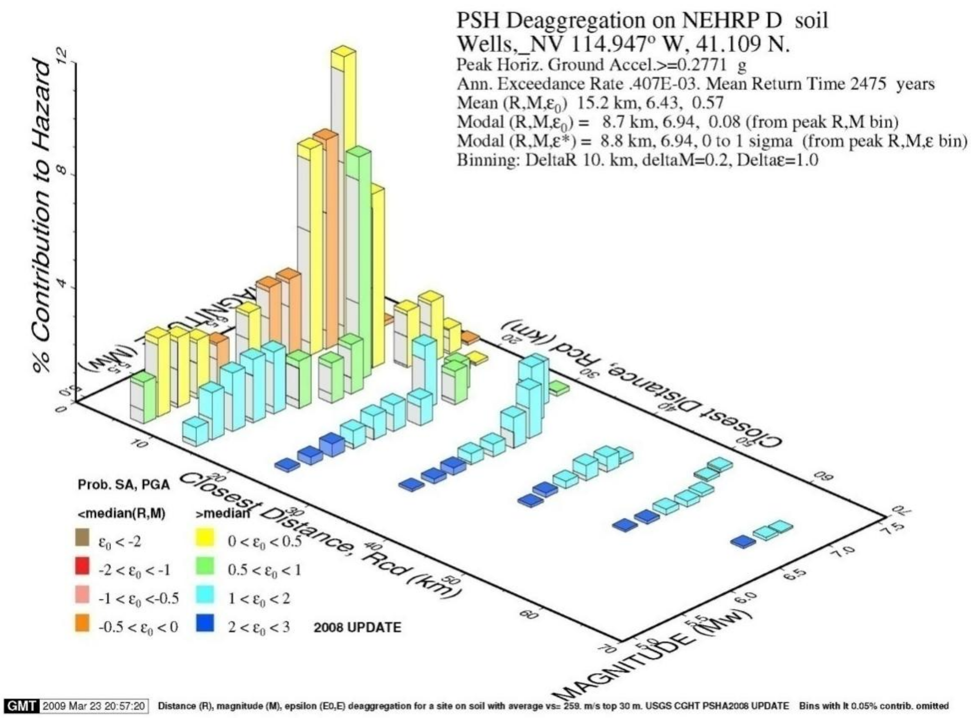

Figure 3. Deaggregation of NSHM seismic hazard at Wells, NV for peak ground acceleration at 2% probability of exceedance in 50 years on uniform D soil class. Shown are the contributions from magnitude, closest distance, and epsilon - difference between ground motion and mean ground motion for that magnitude and distance. The deaggregaion calculator may be found at http://earthquake.usgs.gov/hazmaps/.

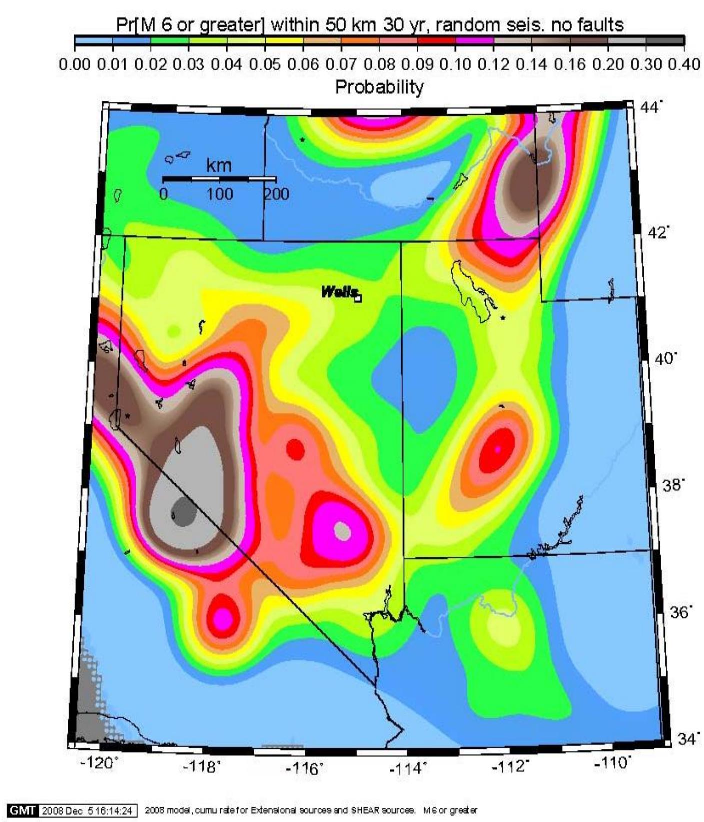

Figure 4. Probability of M 6 or greater earthquake within 50 km of the site within a 30-yr time interval (time independent) based on the calculator found at http://earthquake.usgs.gov/hazmaps/

OBSERVED GROUND MOTIONS

The M 6.0 Wells, Nevada earthquake occurred on a normal fault dipping about 55 degrees to the southeast, with aftershocks recorded in an orientation similar to the north-trending basin edge (Smith and others, this volume). Aftershock mechanisms were mostly normal, but strike-slip mechanisms were observed in the northern portion of the aftershock region (Herrmann, 2008). Mendoza and Hartzell (2009) inverted three-component waveforms from aftershocks using empirical Green's functions to infer a fault patch that extends about 4 km along the strike and 6.5 km downdip with a stress drop of 72 bars. They suggest that this stress drop is higher than expected for Basin and Range normal faults in the western U.S. (Mendoza and Hartzell, 2009).We collected ground shaking data from the mainshock for PGA and computed 0.2 s and 1 s spectral acceleration to compare with the new NGA GMPEs (figure 5a-c). The median and uncertainties in the Campbell and Bozorgnia (2007) GMPE curves for a M 6.0 event are compatible with the observed mainshock data out to 200 km, the range of distances for which the curves were developed. At distances farther than 200 km, which were not modeled in the NGA equations, the ground shaking data is systematically lower than predicted ground motions from the NGA equation for PGA and the two spectral periods. Several strong motion recordings fall below the two sigma levels of this ground motion model. In addition, the slope of the data seems to decay faster than the NGA equation resulting in an overprediction by the equations at larger distances.

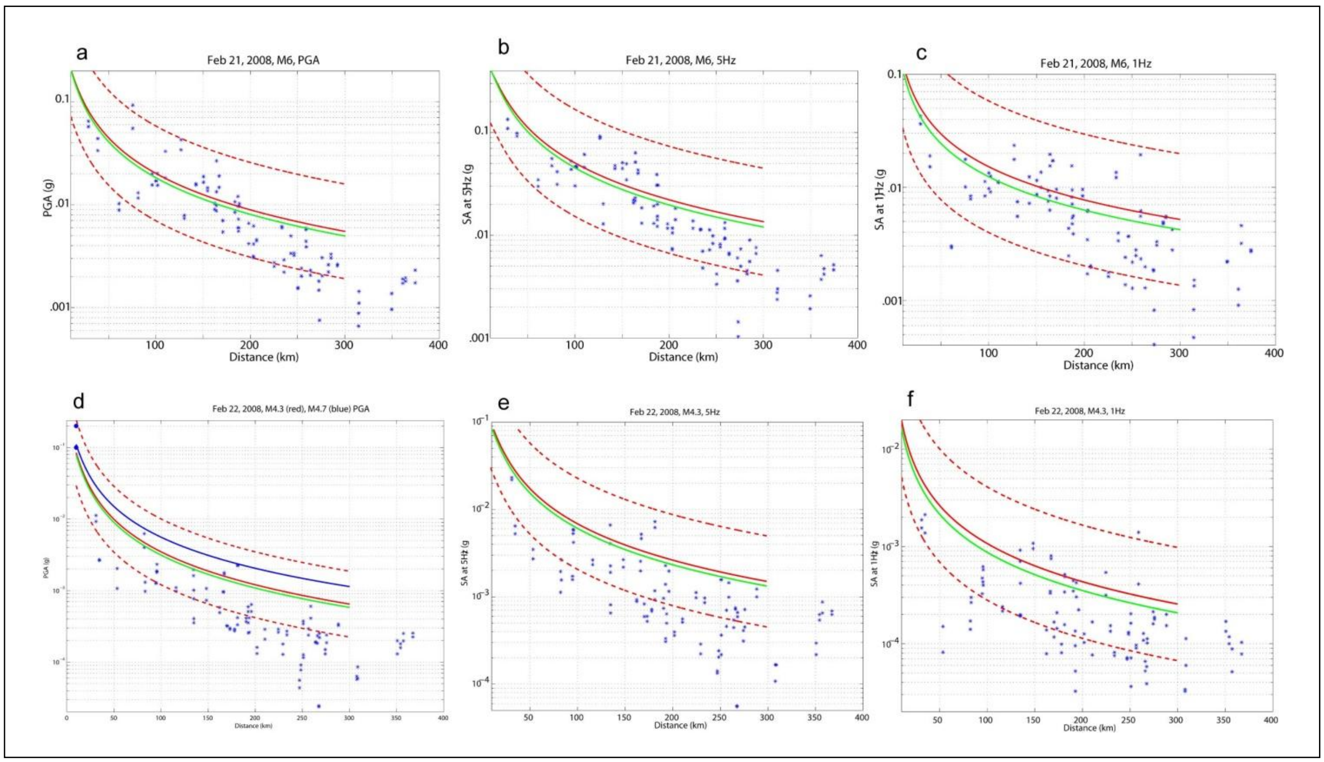

Figure 5. Comparison of the Campbell and Bozorgnia (2008) NGA equations for two types of alluvial soil Vs30= 270 m/s (red curve) and Vs 30=360 m/s (green curve) with observed ground motions from the mainshock (top row, a-c) and the February 22, 2008 aftershock (bottom row, d-f) for peak ground acceleration (pga) and spectral acceleration at 5 Hz and 1 Hz. Red dashed lines represent 2 sigma confidence levels. In all of these plots the middle red and curves represents the median ground motion for a M 4.3 event. Plot d, blue line shows the median ground motion for M 4.7 to compare with red line for a M 4.3 event. Both of these magnitudes have been computed for this aftershock. While the lower magnitude M 4.3 ground motion predictions are more consistent with the ground motion data, many of the data still fall outside the 2 sigma levels. The two larger blue dots in plot d at distances less than 50 km represent the peak accelerations shown in figure 7.

The M_W 6.0 Wells earthquake ground motions were not recorded at distances less than about 37 km from the hypocenter. In response, the University of Utah, University of Nevada, and the USGS deployed 27 temporary digital (23) and analog (4) stations (Smith and others, this volume). These stations were deployed primarily at free-field locations but also included two building sites within the city of Wells, NV. To facilitate timely analysis, 16 stations, including the four analog stations, were set up with telemetry to record real-time weak- and strong-motion data. Stations were arranged in a pattern to better analyze the source characteristics of normal faulting within the Basin and Range province as well as site response and wave-propagation effects in the Town Creek Flat basin (figure 6).

Peak ground acceleration and spectral accelerations (0.2 s and 1 s period) from an aftershock of the Wells earthquake on Feb 22, 2008 are shown in figure 5 (d-f). The Reno catalog (Smith and others, this volume) indicates a M of 4.7 while Herrmann (2008) calculates a M 4.3; the reason for the discrepancy is unknown. In general, the ground motions appear to be lower than expected from the Campbell and Bozorgnia (2008) GMPE. However, at the Wells Fire Station located 13 km from the rupture source on a soil site, the ground motions appear to be anomalously high (see figure 5c-blue dots). This ground motion was recorded on a portable instrument deployed by the University of Utah (Kinemetrics Etna). Strong motion recordings indicate that shaking at the site exceeded 0.2 g and experienced sustained accelerations above 0.1 g for about 5 seconds (figure 7). The fire station strong-motion instrument was re-checked for instrumental or processing problems, none were recognized. These aftershock ground motions are closer to the level of expected shaking from the mainshock and are capable of causing damage to poorly designed structures. The Campbell and Bozorgnia (2007) GMPE predict median peak ground accelerations of about 0.07 g for a magnitude 4.7 earthquake at 13 km distance on soil site conditions, which is lower than amplitudes observed on seismograms shown in figure 7. Similar to the mainshock ground motions, many of the recorded aftershock ground motions are more than two sigma levels lower than the median predicted from the Campbell and Bozorgnia (2007) GMPE (figure 5). They also show a steeper decay rate than the equations would indicate.

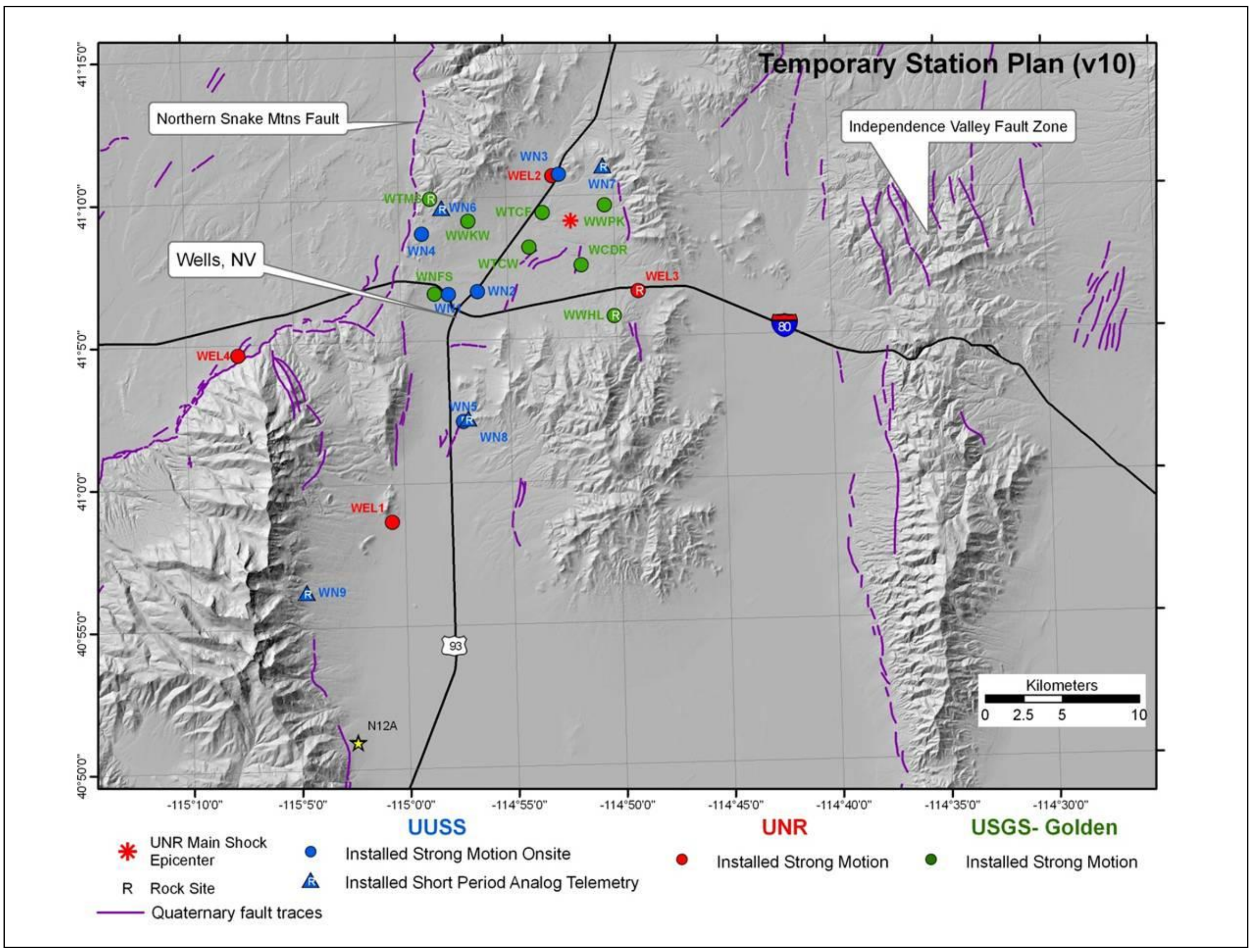

Figure 6. Map of the Wells, NV earthquake epicentral region showing locations of stations deployed to record aftershock ground motions. Figure from Smith and others (this volume) and the University of Nevada, Reno website: http://www.seismo.unr.edu/

To better understand the potential source and waveform propagation contributions to high ground motion from the Wells aftershock, we examined their Fourier amplitude spectra. The February 22, 2008 M 4.7 aftershock waveforms and related Fourier spectra are shown in figure 7. We computed a least-squares fit of a Brune ω-squared model to the observed acceleration spectrum to assess the corner frequency and moment magnitude. The average corner frequency for the three components is 1.9 Hz and the average moment magnitude is 4.7, suggesting an average stress drop of 220 bars. This stress drop seems high when one considers the ground motions recorded at more distant stations (figure 5). In addition, the stress drop from this aftershock is higher than typical stress drops observed in the Basin and Range Province. This event may be atypical of earthquakes in this region but further studies should be conducted to evaluate the stress drops from these aftershocks. High amplitudes of the spectrum for the east component relative to the Brune model (e.g., Humphrey and Anderson, 1992) may indicate site effects are important at that site, especially in the 3-5 Hz resonance frequency range.

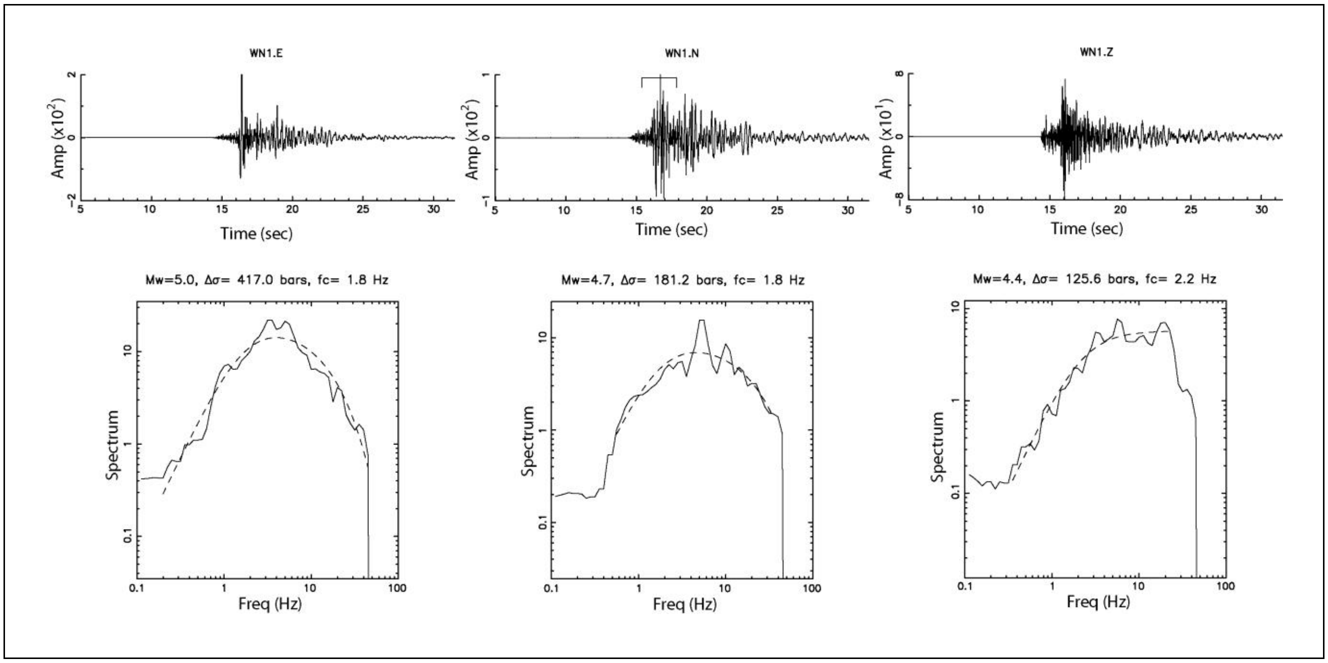

Figure 7. Seismograms of the February 22, 2008 aftershock of the Wells, NV earthquake at Wells Fire Station (University of Utah). Ground motions are shown in units of cm/s^2. Top plots show acceleration records for the E, N, and vertical (Z) components. The bar above the N component is the window used for calculating the Fourier spectra. Corresponding Fourier spectra (with units of cm/s) are shown below with the best fit Brune model prediction.

The mainshock was widely felt not only in Nevada, but also in Idaho and along the Wasatch Front in Utah. Advanced National Seismic System stations in the Salt Lake Valley (SLV), UT, located about 250 km from the mainshock, recorded ground motions of almost 1% g (figure 8). The maximum ground motions recorded in the SLV were located near the center of the sedimentary basin on sediments with average shear velocities in the upper 30 m (Vs30) less than 200 m/s. Ground motions on the edges of the basin (Vs30 > 400 m/s) were much lower. For example, ground motions in the center of the basin (figure 8) are about a factor of two to three times higher, on average, than ground motions recorded on the adjacent mountain flank sites. Even after correcting for site amplification factors (Borcherdt, 1994) corresponding to mapped Vs30 units (McDonald and Ashland, 2008) ground motions in the central and northeast corner of the SLV remain higher than ground motions recorded on the valley edges (figure 8). This observation suggests that basin response may be important in amplifying the ground motions.

The sediments in high amplification areas of the SLV are typically 0.5 to 1 km thick. For example, Stephenson and others (2007) imaged sedimentary deposits up to 1 km depth in the central portion of this basin using reflection and refraction data collected from a vibroseis source. The northeast corner of the SLV has mapped unconsolidated sediment depths greater the 0.5 km (Arnow and others, 1970). The corrected ground motions for rock sites on the west side of the valley are also high most likely indicating that the Vs30 estimates are too high (there is no current Vs30 data for these rock sites). The Wells seismograms that were recorded in the Salt Lake City area suggest more work is necessary for estimating site effects and sedimentary basin amplifications from future large earthquakes located near the Salt Lake Valley.

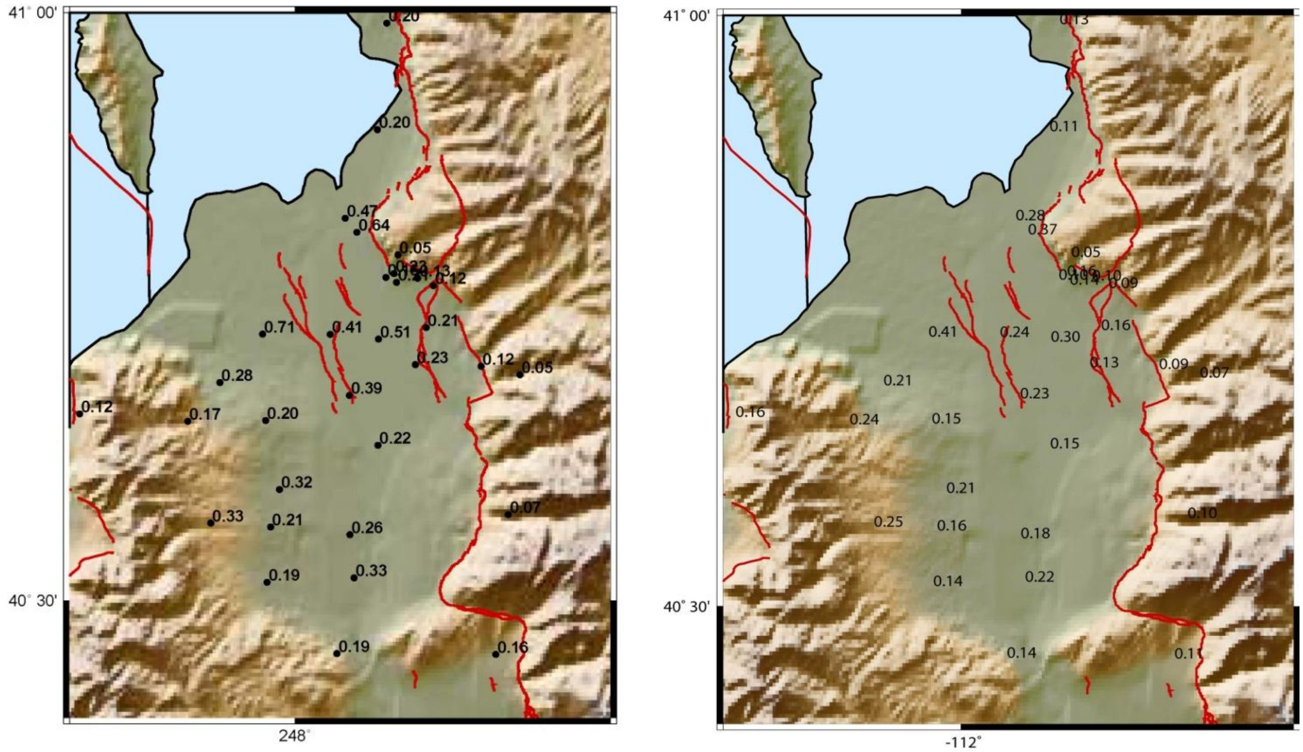

Figure 8: (A) Maximum peak horizontal ground acceleration in Salt Lake Valley (in % g), Utah from the February 21, 2008 Wells, Nevada earthquake. Red lines delineate faults in the region. (B) Corrected peak horizontal ground acceleration using Borcherdt (1994) correction factors calculated for the Salt Lake Valley.

DISCUSSION AND CONCLUSIONS

The Wells, NV earthquake provides important information on characteristics of ground shaking from future earthquakes in the Intermountain West region. This information can be used to update the seismic hazard maps.

1. Fault mechanism is an important factor in calculating ground motions. In the national map model we include background earthquakes using 50% normal and 50% strike-slip mechanisms on a fault with a random strike orientation. The Wells, NV earthquake and its aftershocks were mostly comprised of normal faulting mechanisms that align in a northeast trend. Perhaps a higher percentage of normal faulting earthquakes should be included in the model with the preferred strike direction being consistent with the regional stress field or range fronts.
2. Fault dip is an important parameter in estimating hazard since it is used to calculate the distance from a site to a source and is used to calculate the moment rate available for earthquake ruptures. In the national map model we used faults with dips ranging from 40 to 60 degrees with 50 degrees having the highest weight. This was consistent with the 55 degree SE oriented dip of the mainshock as defined by the aftershocks (Smith and others, this volume).
3. Moderate to large earthquakes and their aftershocks can generate high ground accelerations that are similar to the levels observed in mainshock ground motions. For example, the M 4.7 aftershock caused 0.2 g PGA on a soil site. Aftershock ground motions may contribute to the seismic hazard, but are not currently considered in seismic hazard maps. They may also contribute to damage following the mainshock.
4. Ground motion prediction equations may not provide accurate estimates at distances beyond 200 km or for earthquakes smaller than M 5.0. The current equations are only valid at distances less than 200 km.
5. Basin effects should be considered in future urban hazard maps. Site amplification at the Wells Fire Station and the Salt Lake Valley both are important factors in determining ground shaking. For example, the Fourier spectrum of the aftershock at the fire station provides evidence that site effects with a resonance frequency of about 3 Hz may have contributed to the high ground shaking. Amplified ground shaking was also observed within the SLV. Although much of the amplification in the SLV is explainable with Vs30 site amplification factors, in the central

part of the valley on the slowest soils there is a suggestion that the site amplification factors are underestimated or that other basin effects are contributing to the ground motions. Currently the seismic hazard maps do not consider these effects due to lack of data. This ground shaking information should be analyzed for developing urban hazard maps. Finer spaced seismic instrumentation across the Intermountain West region would provide data for infrequent earthquakes and refine our estimates of ground motion uncertainty.

6. In the Wells earthquake sequence it appears that the mainshock and the aftershocks had higher than average stress drops. The mainshock stress drop was calculated as 72 bars by Mendoza and Hartzell, (2009) and 89 bars by Smith and others (this volume) while we calculated a Brune stress drop of 220 bars from one M 4.7 aftershock that occurred a day after the mainshock. Variability of ground motion and stress drop are important considerations in developing models for seismic hazard. Stress drops should be evaluated for other aftershocks to observe whether or not this event was typical of extensional-fault earthquakes.

The 2008 Wells, NV earthquake caused significant damage in a town that had previously experienced only a few moderate size earthquakes in the historic record. This area is similar to many regions of the Intermountain West that are characterized by numerous mapped faults but moderately-low seismicity and strain rates. The Wells earthquake indicates the importance of area sources in the seismic hazard model in accounting for moderate to large size earthquakes on unknown geological structures. These earthquakes are important components of any seismic design considerations in which the primary goal should be to minimize casualties from future earthquakes.

ACKNOWLEDGMENTS

We thank all those from University of Utah, University (Jon Rusho, J. Mark Hale, Dave Drobeck, Ken Whipp, and Jim Pechmann) of Nevada-Reno (Ken Smith, Nathan Edwards, Austin Wilson, John Torrisi, David von Seggern, and Rasool Anooshehpoor, and USGS (James Allen, Jeff Fox, Martin Messmer, and Steve Ploetz) that participated in collecting and analyzing the aftershock data. We also thank Steve Hartzell and Art Frankel for useful discussions and Bill Stephenson and Rob Williams for helpful reviews of the manuscript.

REFERENCES

Allmann, B.P. and Shearer, P.M., 2009, Global variations of stress drop for moderate to large earthquakes: Journal of Geophysical Research, v. 14, B01310-B01310.

Arnow, T., Van Horn, R., and LaPray, R.,1970, The pre-Quaternary surface in the Jordan Valley, Utah: U.S. Geological Survey Professional Paper 700, p. D257 –D261.

Borcherdt, R.D., 1994, Estimates of site-dependent response spectra for design (methodology and justification): Earthquake Spectra, v. 10, p. 617–654.

Campbell K.W. and Bozorgnia, Y., 2007, NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s; Earthquake Spectra, v. 24, p. 139–172.

dePolo, C. M., *this volume*, Building Damage from the 2008 Wells, Nevada Earthquake.

Herrmann, R. 2008, www.eas.slu.edu/People/RBHerrmann

Humphrey, J.R., Jr., and Anderson, J.G., 1992, Shear-wave attenuation and site response in Guerrero, Mexico: Bulletin of the Seismological Society of America, v. 81, p.1622–1645.

McDonald, G.N., and Ashland, F.X., 2008, Earthquake site conditions in the Wasatch Front urban corridor, Utah: Utah Geological Special Study 125, p. 41, 1 plate, scale 1:150,000, compact disk.

Mendoza C. and S. Hartzell 2009, Source analysis using regional empirical Green's functions–The 2008 Wells, Nevada, earthquake: Geophysical Research Letters, v. 36, L11302.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E. H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 Update of the United States National Seismic Hazard Maps: USGS Open-File Report 2008-1128, p. 60, 11 appendices.

Smith, K., Pechmann, J., Meremonte, M., and Pankow, K., *this volume*, Preliminary analysis of the M_w6.0 Wells, Nevada, Earthquake Sequence.

Stephenson, W.J., Williams, R.A., Odum, J.K., and Worley, D.M., 2007, Miscellaneous high-resolution seismic imaging investigations in Salt Lake and Utah Valleys for earthquake hazards: U.S. Geological Survey Open-File Report 2007-1152, p. 29.