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An Introduction to the February 21, 2008, M_w 6.0 Wells Nevada Earthquake and the Earthquake Documentation Volume

by

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INTRODUCTION

The Wells, Nevada earthquake occurred at 6:16 a.m. PST (14:16 UTC) on February 21, 2008 in northeastern Nevada, a region that had not had many earthquakes historically and lacked permanent seismometers to record events (figure 1). The earthquake had a moment magnitude of 6.0, an epicenter about 9 km (6 mi) northeast of the City of Wells, and ruptured in the subsurface to within a few kilometers of the community. After a universally heard large "bang" sound, Wells residents rode out the earthquake for as long as 40 seconds. Some stayed in bed, some sat or stood in place, some scrambled for their lives and ran out of their residences, and some protected possessions (such as one resident who reported steadying his giant flat-screen television). At the early morning hour of the event, nobody was in harm's way along the sidewalks of the historical district, and fortunately there were no deaths and only three minor injuries from the earthquake. The strong shaking caused at least minor damage to over 40 commercial and government buildings, roughly half the non-residential buildings in Wells, and major damage to 17 buildings (figure 2). There was damage to over 60 chimneys in Wells, which was 10% to 15% of all the chimneys in town, and there was widespread nonstructural damage that included cracked interior drywall and windows, and fallen and damaged pictures, televisions, fish tanks, and dishes, in Wells and surrounding areas.

The cost of the earthquake, including the emergency response, damage losses, and reconstruction, was over $10.5 million. For some folks in Wells, the impact of the earthquake was the effort involved in cleaning up the home and work place and lending a helping hand to others. They lost some items and had cracks in the interior drywalls of their houses. A few others, however, lost their homes and had to deal with living in hotels and a very uncertain future. And, as can happen from earthquakes, a couple of people had complete changes in their livelihoods. In the moments, hours, days, weeks, and months thereafter, people worked tirelessly to respond to the emergency and recover from the earthquake. The community returned to a certain sense of normalcy within about year, was largely recovered within about three years, and has steadily tried to resolve outstanding damage.

Scientifically, we were fortunate to have had a temporary, multi-state seismic network, called the EarthScope USArray network, operating in Nevada at the time of the Wells earthquake that recorded foreshocks, the mainshock, and aftershocks with high-quality instruments. The region has always been poorly instrumented, but this National Science Foundation experiment had been operating for about a year prior to the event and continued operating for about six months afterwards. Seismologists from the Nevada Seismological Laboratory, the University of Utah Seismograph Stations, and the U.S. Geological Survey rapidly installed additional seismic instruments that recorded aftershocks and ground motion in the damaged historical district. The aftershocks were relocated precisely, imaging the earthquake rupture plane (Smith and others, this volume). The Wells earthquake occurred on a previously unmapped fault strand that would likely have been difficult to detect before the earthquake, although parts of the fault zone to which it belongs were mapped elsewhere. The upper part of the earthquake appears to have died out below the ground surface, making it a "blind event." The normal dip-slip earthquake occurred below the Town Creek Flat sedimentary basin, on a fault that was oriented N40°E and dips to the southeast at about 55° (Smith and others, this volume). An analysis of measurements made from satellites (Bell, this volume) shows that the ground surface over the earthquake in Town Creek Flat fell by as much as 15 cm (~ 6 in) during the sequence; this is an example of some of the remarkable measurements that have been made to enable a better understanding of the Wells earthquake.

Earthquakes in Nevada
1840s to 2009

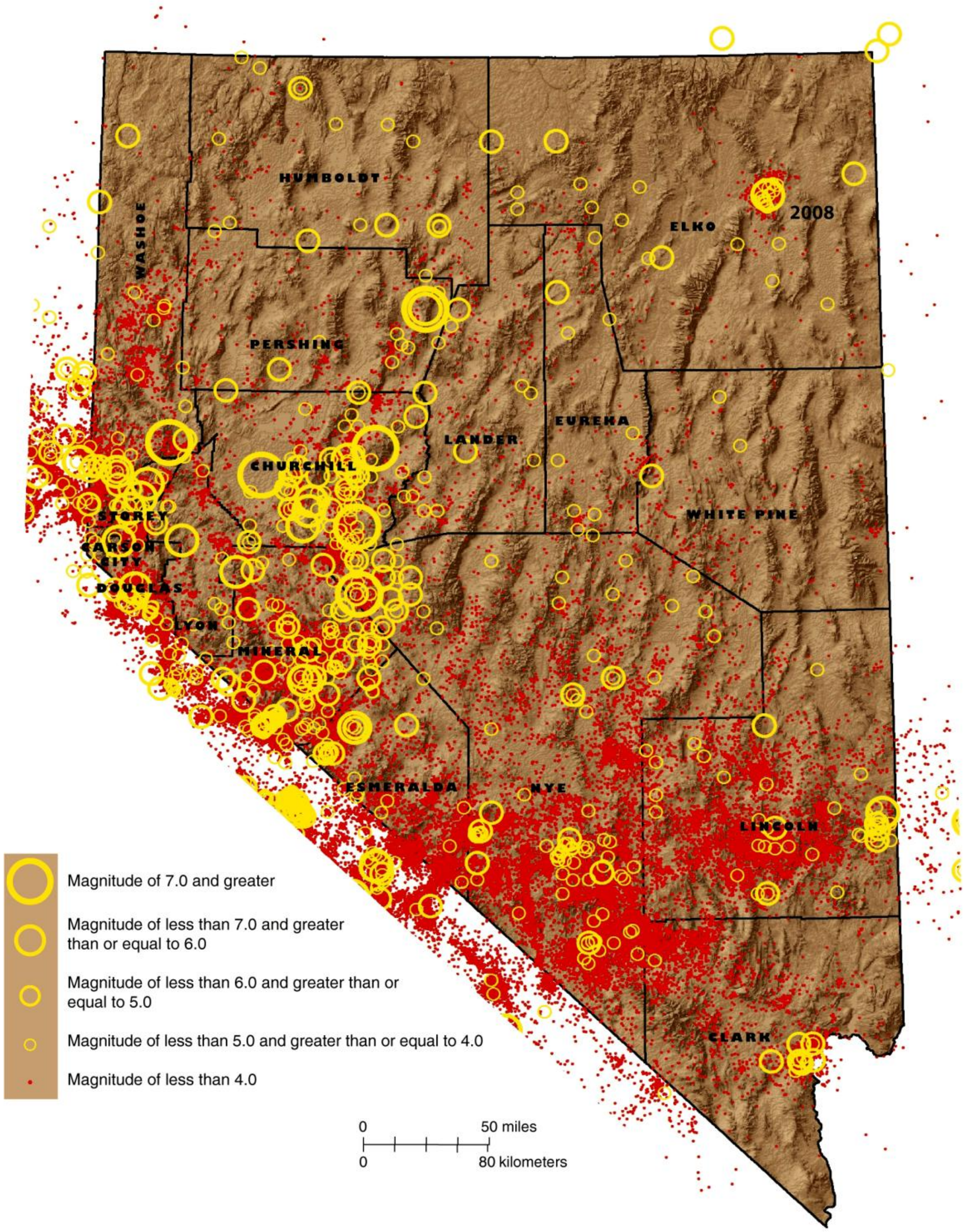

Figure 1. Seismicity map of Nevada. Note the quieter seismic activity in the northeastern part of the state. The 2008 earthquake is labeled and the smaller earthquakes around the magnitude 6 event are aftershocks from the Wells earthquake. The earthquake data have been collected and cataloged by the Nevada Seismological Laboratory.

Figure 2. Wells historical district, where several unreinforced masonry buildings were damaged by the 2008 earthquake.

Several scientists have reported on their findings in this volume, giving an excellent background, perspective, and understanding of the earthquake. It includes reviews of the local geological and seismological settings and a detailed analysis of the event itself. The damage to buildings and utilities and the effects on the community have been described, along with numerous recommendations on successfully surviving earthquake disasters. This information can benefit all communities in the areas of earthquake preparedness, earthquake risk mitigation, earthquake engineering, earthquake disaster response, earthquake recovery, and the science of earthquakes.

THE CITY OF WELLS

Wells is a northeastern Nevada community of about 1650 people who live in and adjacent to the town (figure 3). It is an incorporated city with a public works department, a medical clinic, and a volunteer fire department. Law enforcement services are contracted with the Elko County Sheriff. There are about 450 residential homes and about 80 nonresidential buildings in town. There are multiple-generation residents and new residents. Wells lies at the intersection of Interstate 80, U. S. Highway 93, and the Union Pacific Railroad, and supports both tourist and long-haul cargo traffic along these major transportation routes. Economically, Wells also supports several government agency offices, cattle ranching, and regional recreational activities. The townsfolk from Wells are a hardy, can-do people, who retain their pioneering sense of survival and fortitude.

Wells grew along the transcontinental railroad as a watering stop for steam engines and later as a rail yard where engines were added to help the weaker diesel trains climb a local grade. The first permanent building in Wells was the Bullshead Bar, established in 1869. The historical district was built parallel to the railroad tracks, and some buildings were partly built out of track ties and other material related to the railroad.

When U. S. Highway 40 was built across the nation, it went through Wells, one block south of the railroad tracks. Where it intersected Highway 93 on the east side of town was a noted four-way stop. Significant commerce developed in these areas to support travelers including gas stations, restaurants, garages, and motels. When Interstate 80 was built, it (and much of the cross-country traffic) bypassed the town, although commerce has developed around the freeway off-ramps. These and other changes have led to boom and bust cycles in Wells, which have affected building construction, maintenance, and occupancy.

Wells is located at 5640 ft elevation, near the southern end of a small valley known as Town Creek Flat. The flat is bounded by the Snake Mountains on its western side, the Windermere Hills on its northeastern side, the East Humboldt Range on its southwestern side, and Wood Hills on its southeastern side. Winters are fairly severe in Wells with common sub-freezing temperatures, frozen ground, and snow cover.

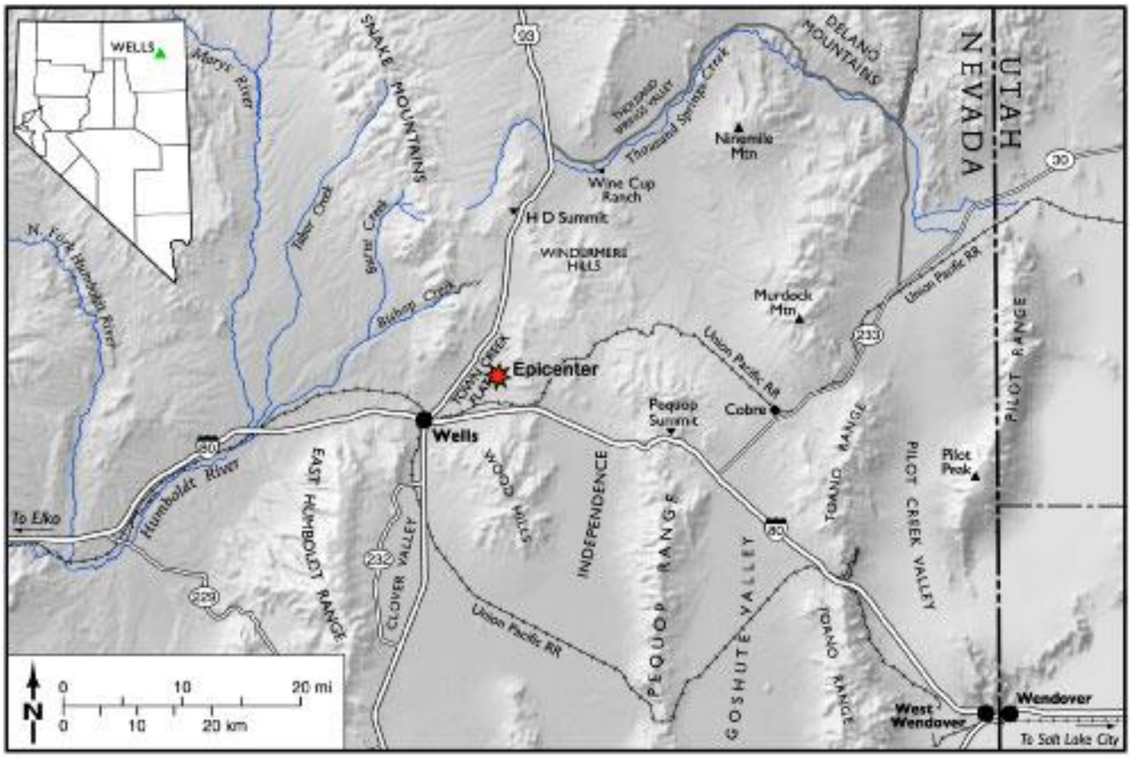

Figure 3. Location of Wells, Nevada and the epicenter of the 2008 Wells earthquake.

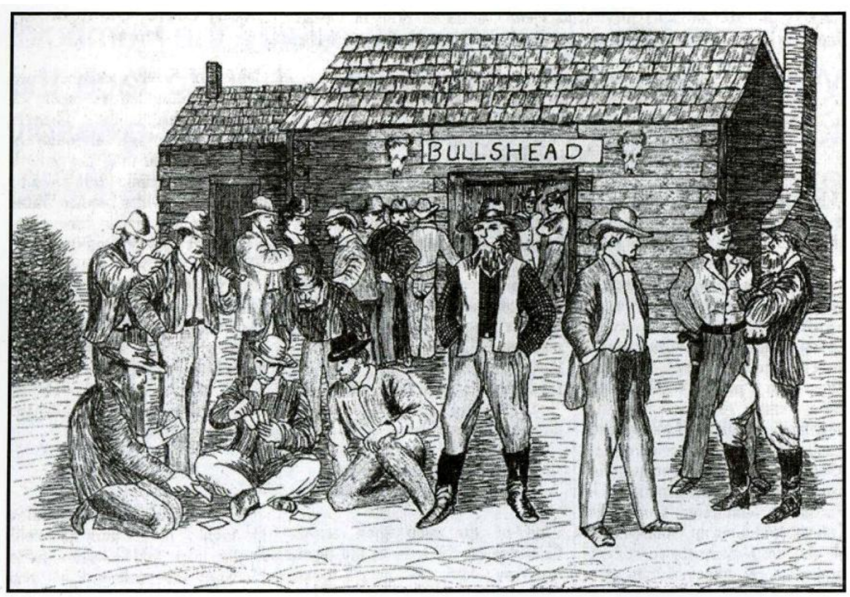

Figure 4. Wells artist Sue Chapman portrays the early Bullshead Bar, shown here in spring of 1870, redrawn from a 19th century sketch.

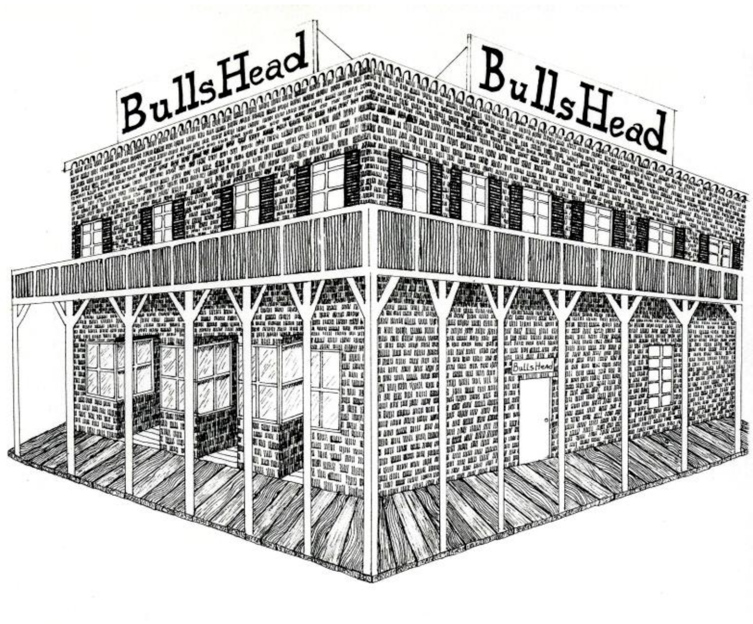

Figure 5. Sue Chapman's rendition of the modern Bullshead building that was damaged in the 2008 earthquake.

Figure 6. Front Street of the Wells historical district during the bustling 1930s. Ranchers, motorists, and townsfolk enjoyed the cafes and saloons. Picture from the "Old Town Front Street Walking Tour"–The Wells Society for Preservation of Western Heritage.

Wells government and residents were prepared to handle disasters. The Wells city government and the school district had earthquake insurance. Local and regional emergency responders were professionals, knew how to handle emergency situations, and had worked together previously on wild-land fires. Wells residents were taught to respect propane gas but not fear it, and were instructed in how to turn off their gas if they smelled a leak. But the belief that "earthquakes could happen here" wasn't generally embraced in Wells before the earthquake. In a few instances, people had reviewed small-scale national hazard maps and concluded that the level of earthquake hazard in Wells was too low to be of concern.

Figure 7. Damage to the Bullshead Bar from the 2008 Wells earthquake. Brick veneer fell from the second story along with a crowning concrete bond beam, which both smashed the balcony to the ground. *Photograph by Nick Stake*.

THE 2008 WELLS EARTHQUAKE

On the Thursday morning of the earthquake, and over the days that followed, temperatures were around 20° to 30° F and there were intermittent snow flurries. It had been much colder and about 5- to 50-cm (2- to 20-in) of packed snow covered the ground where it hadn't been cleared. The ground was generally frozen from a few to several decimeters depth. These are some of the most challenging conditions there are for people during an earthquake disaster, such as staying warm when outside and driving on icy roads. Fortunately, most people were able to stay in the undamaged houses because the electricity stayed on, and most gas connections to propane tanks, the tanks themselves, and home heaters were in good shape, as were most windows.

A timeline of the earthquake shaking was developed from observing security cameras at Stuarts Market. Pictures normally were recorded every few seconds, but the cameras were equipped with motion detectors and recorded semi-continuously when they sensed motion. All cameras indicate "motion detected" at the beginning of the earthquake. Over the first 1.5 seconds, five vertical pulses can be seen, which are likely primary body waves (P-waves). Over the next 1.7 seconds, lateral, or side-to-side, waves are seen that throw a few objects off the shelves; these are shear waves (S-waves). The strongest shaking begins about 3 seconds into the earthquake and shuts the entire camera recording system down for 12 seconds, but when the next frame appears merchandise is on the ground and the ceiling tile system of the store has been damaged. Lateral shaking waves are seen for about 8.4 seconds more and then things calm down but are still shaking with lower amplitudes for about another 21. 3 seconds; this calmer shaking is likely from seismic waves that were trapped in Town Creek Flat sedimentary basin and the adjacent Marys River sedimentary basin. The timeline strongly supports reports from Wells citizens that shaking occurred for 40 seconds. It also indicates there was very little time from the start of shaking until the strongest shaking—maybe a little over 3 seconds, in which to decide to act and engage in a drop, cover, and hold maneuver. This short time interval was because the earthquake was right next to Wells. The strongest waves, and likely most of the damage, occurred within a 12-second period beginning about 3 seconds after the start of the earthquake.

Table 1. Earthquake Shaking Timeline (Stuart Market Security Camera)

Seconds	Shaking Effect
0	start of earthquake
0-1.3	five vertical pulses
1.3-3	lateral wave pulses, some objects thrown
3-15	strongest ground motion, many objects thrown
15-23.4	moderate lateral shaking
23.4-45	calmer shaking – basin response

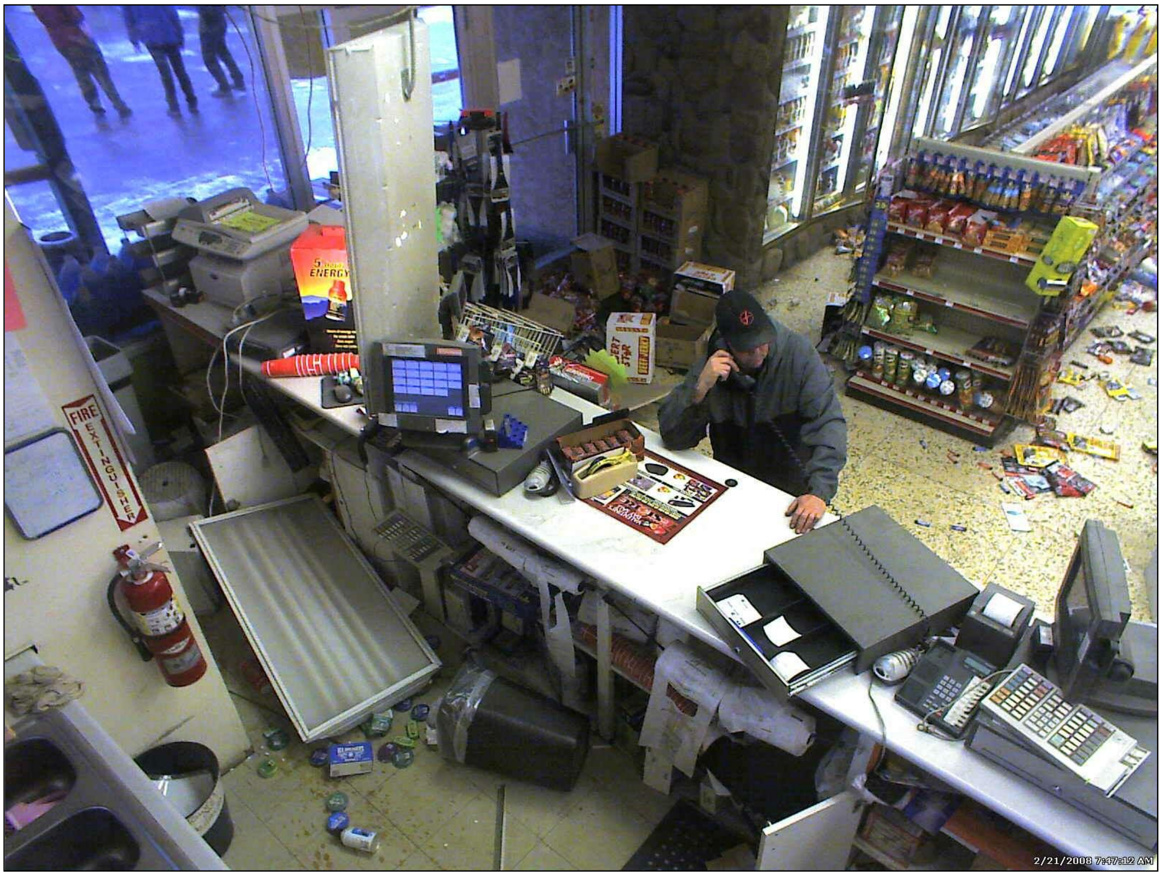

Figure 8. Nonstructural damage at the Flying J Truck Stop. Ceiling lights that had fallen are seen as well as fallen contents. *Photograph from surveillance camera*.

Damage to the buildings in Wells, particularly in the historical district, was typical for unreinforced masonry construction: collapse and partial collapse of buildings, fallen sections of walls and parapets, detached and rotated roof systems, delaminated brick walls, fallen crowning concrete bond beams, and large shaking cracks. Three houses were lost, principally due to foundation damage and damage at connecting points. There were breaks in a water main, a small "elephant's foot," or bulge, at the base of a large municipal water tank, and three propane leaks, two of which were gas and one which was a liquid propane leak. There was a small house stove fire started by the earthquake, which was immediately extinguished by the residents. There were some major losses of contents and stock from the earthquake, and several buildings had nonstructural damage, such as damage to their ceiling systems.

Figure 9. Bricks from an unreinforced veneer and broken glass from the front plate glass window are strewn about a bench on the sidewalk and the building's exit in front of the Overland Hotel. The early morning time of the earthquake helped prevent more injuries and possible deaths.

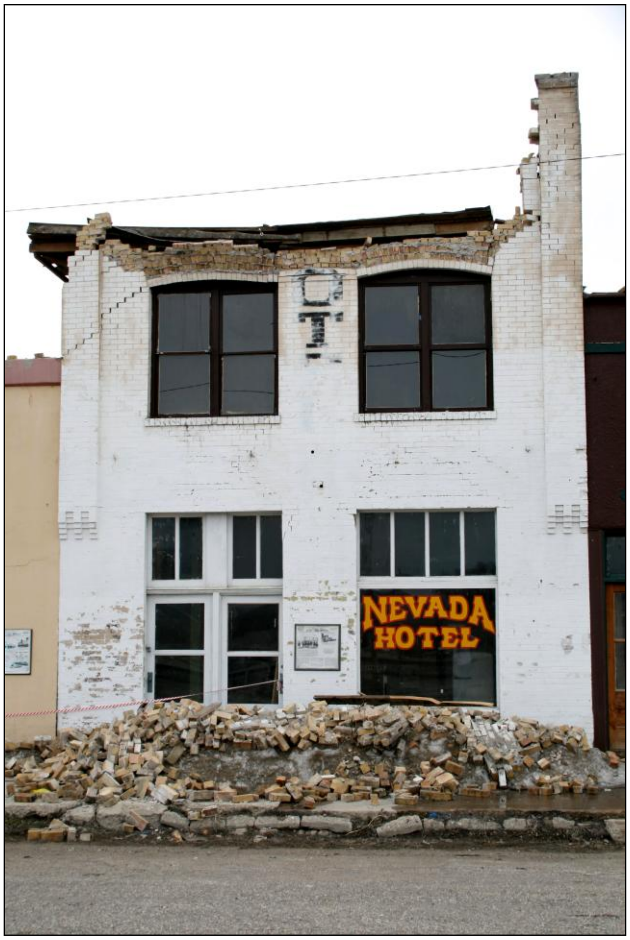

Figure 10. Partial collapse of the Nevada Hotel. Nearly all of the upper parts of the walls and parapets failed, dropping the roof down on the second story ceiling. Many bricks fell across the front exit of the hotel. Remarkably, for all this damage caused by shaking, none of the windows are broken.

Figure 11. Large chimney on side of the Wells High School auditorium that was cracked from the earthquake. Note the bricks that were thrown out as the top of the chimney was cocked back towards the building from the shaking.

The emergency response to the Wells earthquake disaster was admirable. Dedicated, trained, willing, and coordinated men and women reacted in an appropriate and effective manner (figure 12). There were no deaths, only a few minor injuries, and no out-of-control fires or explosions, although the potential for all of these existed. The local emergency responders and technicians handled all the acute situations, and the influx of outside assistance gave depth to the response for safety inspections and other needed activities.

The recovery of Wells from the earthquake has been equally admirable. The residents worked rapidly, and with the help of neighbors and regional friends, they cleaned up their homes and community. Money was donated, a recovery rally was held, State of Nevada programs helped with both the emergency response costs and major losses suffered by several homeowners, and the Small Business Administration made several disaster-assistance loans. The largest financial burden from the earthquake was borne by the Nevada Public Agency Insurance Pool, which covered about $4.8 million of losses, or about 46% of the total losses and costs. This clearly underscores the importance of having earthquake insurance in earthquake country. Aftershocks continued for months, and often rekindled the anxiety felt by residents from the mainshock, but these earthquakes gradually died away.

Figure 12. Firemen check for leaking gases from a manufactured building that had shifted on its blocks. *Photograph by Wells resident*.

Figure 13. Back of a tee shirt sold at the Wells Recovery Rally for relief funds.

The Wells earthquake occurred on what may be a subsurface or blind fault in a right-step or connection between east-facing range-front faults, the eastern Snake Mountains fault and the Clover Hill fault (figure 14). This is considered the same overall fault zone by Ramelli and dePolo (this volume), with the earthquake occurring along a part called the Town Creek section. There are other fault traces along this section as well, one that has a possible small, latest Quaternary fault scarp, indicating a prehistoric surface-rupturing earthquake that may have been larger that the Wells earthquake. So the Wells earthquake fault does not appear to be the main fault in this section, but rather is a secondary fault and was possibly unrecognizable prior to the earthquake. Nevertheless, the earthquake dropped Town Creek Flat down by 15 cm (6 in), as noted by Bell (this volume), contributing to the development of Town Creek Flat basin, even though it was of a background nature and there will be some rebound with time; the question of how important such background earthquakes might be in the development of basins in Nevada is posed by Smith and others (this volume).

The aftershocks of the Wells earthquake were very well recorded by the temporary seismic stations put out by the scientists (with the help of local agencies and divisions). The aftershocks shown in figure 15 were carefully relocated by Smith and others (this volume) and are a key piece of information in understanding the Wells earthquake. Aftershocks are small earthquakes created by the adjustment of the crust to the mainshock, and as such they are a clue to the size of the mainshock and can image the fault along which the earthquake occurred (Smith and others, this volume).

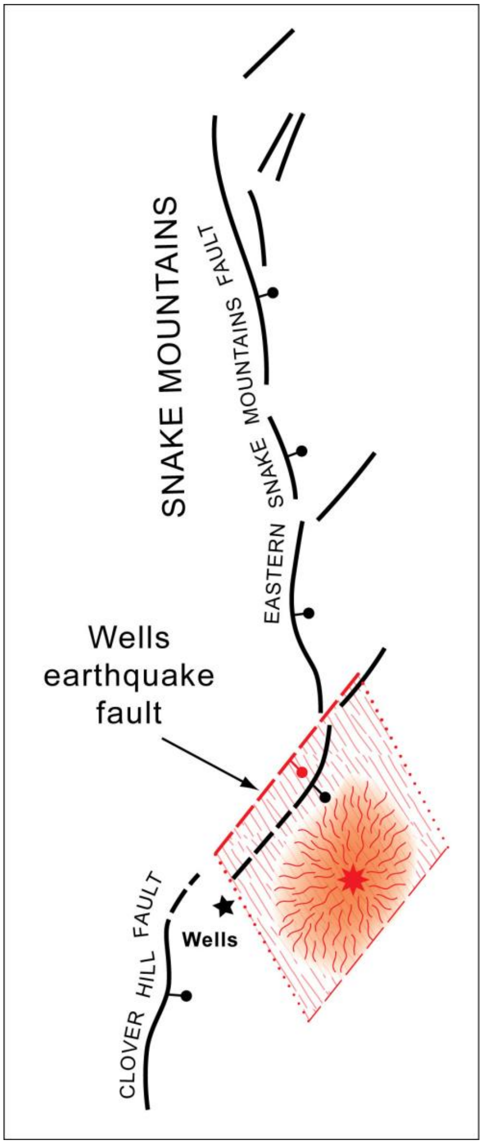

Figure 14. Schematic fault map modified from Ramelli and dePolo (this volume). The Wells earthquake occurred in a right-step connection between the Clover Hill fault and the eastern Snake Mountains fault. The faults are solid where certain and are dashed where they are inferred. The Wells earthquake fault is shown dipping down into the earth in red and a schematic representation of the buried Wells earthquake shown around the hypocenter (red star).

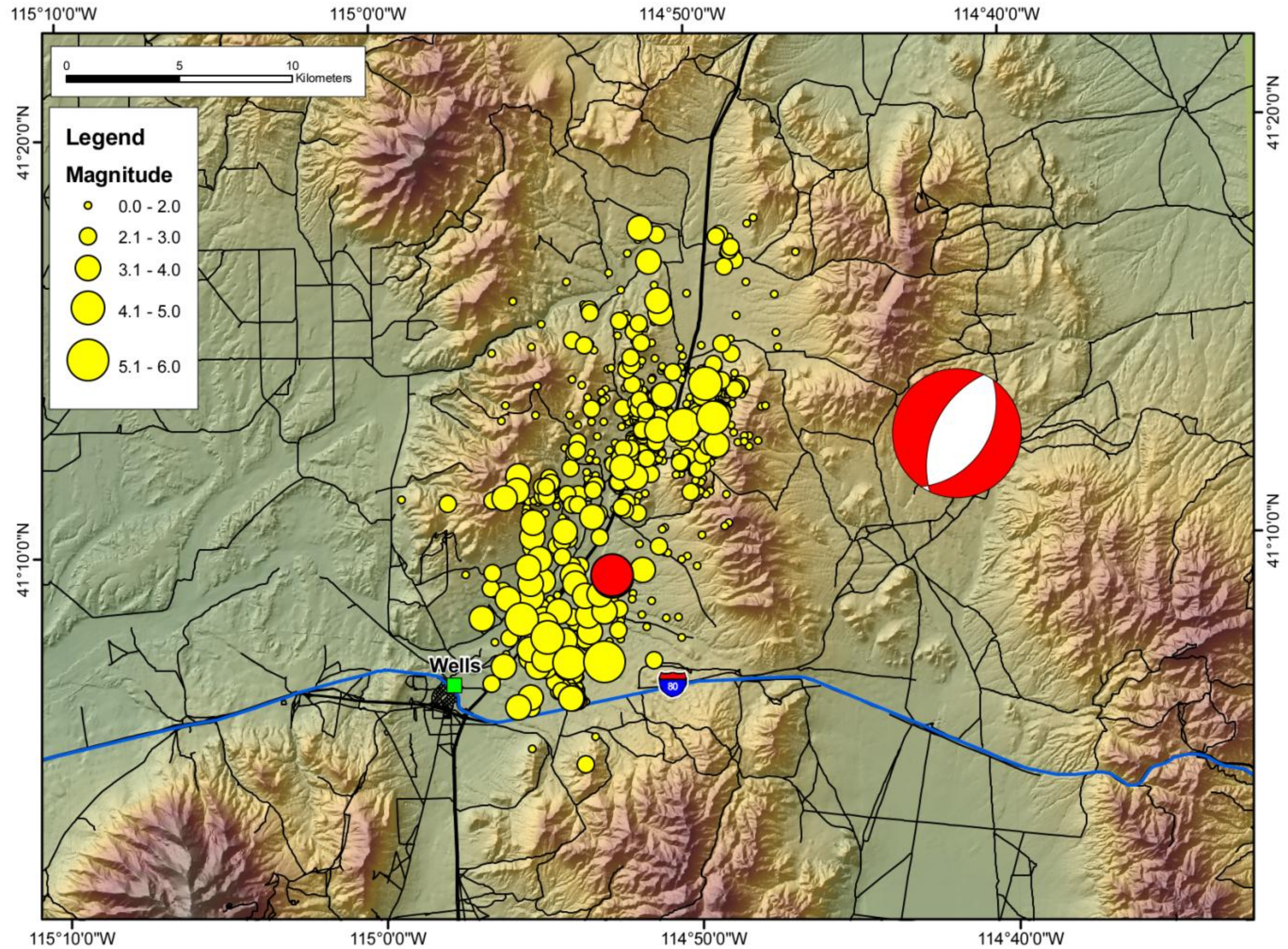

Figure 15. The Wells earthquake sequence relocated by Smith and others (this volume). The solid red dot is the mainshock. Earthquakes on the right side of the swarm are generally deeper than earthquakes on the left side of the swarm, consistent with the southeastward dip of the Wells earthquake fault. The red and white "beach-ball" on the figure is a moment-tensor focal mechanism from Dreger and others (this volume). A focal mechanism is a graphical portrayal of two possible earthquake fault planes based on an analysis of the seismograms recorded from the earthquake. The reference frame is the bottom of a sphere, where the center is the deep part and the sides are the top edge. The lines inside are the trace of a fault plane intersecting the bottom of the sphere, where a vertical fault would have a straight line across, but as the fault begins to have a dip, the intersection of the fault and the sphere bottom becomes a curved line on the side. The red areas are where there would have been compression in the waves going out from the earthquake (the ground would go up at the beginning) and the white area is where there should be dilatation in the first waves going out (the ground would go down in the beginning); these colored areas indicate whether the fault was a reverse or normal slip dip-slip fault. This mechanism is a normal dip-slip one with dilatation in the center, and the aftershock relocations by Smith and others (this volume) indicate that the east-dipping fault, or the curved line on the right, was the fault along which the earthquake occurred.

The Wells earthquake nucleated 8 km (5 mi) below the earth's surface in the north-central part of Town Creek Flat and appears to have rapidly ruptured (approximately at 2.8 km/s or 1.7 mi/s or 6264 mi/hr) in all directions, also called a bilateral earthquake (Smith and others, this volume; Dreger, and others, this volume; Mendoza and Hartzell, this volume). The dimensions and amount of subsurface offset that occurred during the earthquake are modeled in different ways with different data. A more equidimensional rupture 4 to 6 km (2.5 to 3.7 mi) long is modeled by Mendoza and Hartzell (this volume) and Smith and others (this volume), whereas one of the models presented by Dreger and others (this volume) is a more tabular rupture about 14 km (8.5 mi) long. Dreger and others matched the seismograms that were recorded from the Wells earthquake with synthetic ones that help constrain the way the earthquake looked and ruptured in the subsurface (figure. 16). Their preferred model and the aftershocks are shown in figure 17, but keep in mind this is only one of several models that can fit the data. This model shows a patch of the fault that had slip, with the greatest coseismic offset, 103 cm

(~41 in), just to the southwest of the hypocenter. In the early days following the earthquake, there was uncertainty as to whether the earthquake fault dipped to the northwest or the southeast–both dips fit the early data. This kind of modeling by Dreger and others shortly after the event gave us the first information that the rupture dipped to the southeast, an important finding for surface rupture and other investigations.

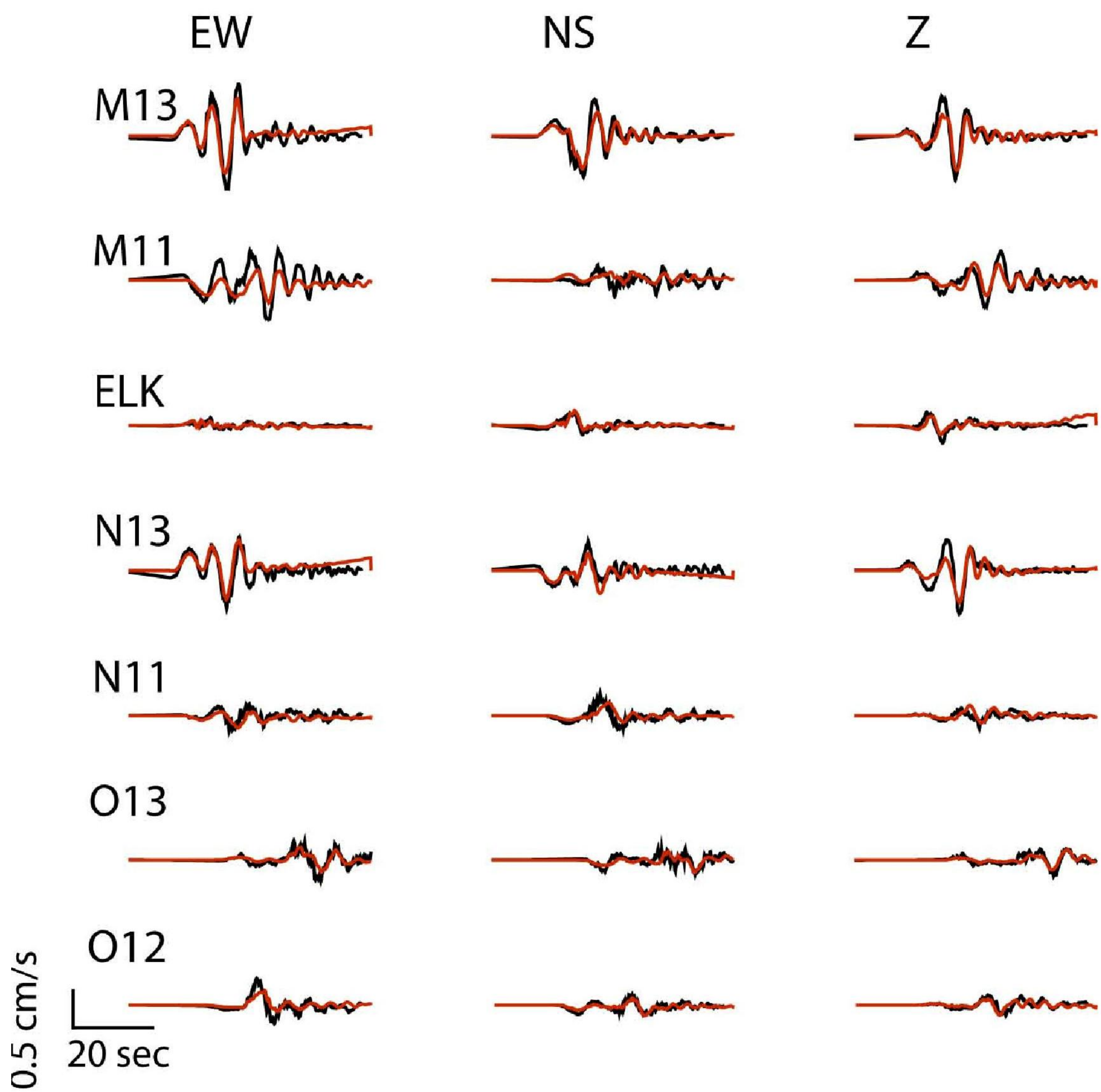

Figure 16. Seismic waves from stations used in modeling the earthquake source by Dreger and others (this volume). The black lines are the recorded seismograms and the red lines are the wave results from the modeled earthquake source shown in figure 17 (please see Dreger and others for further information). The closer the red modeled waves are to the black recorded waves, the more likely the earthquake model is correct. Generally only the main forms of the wave can be modeled.

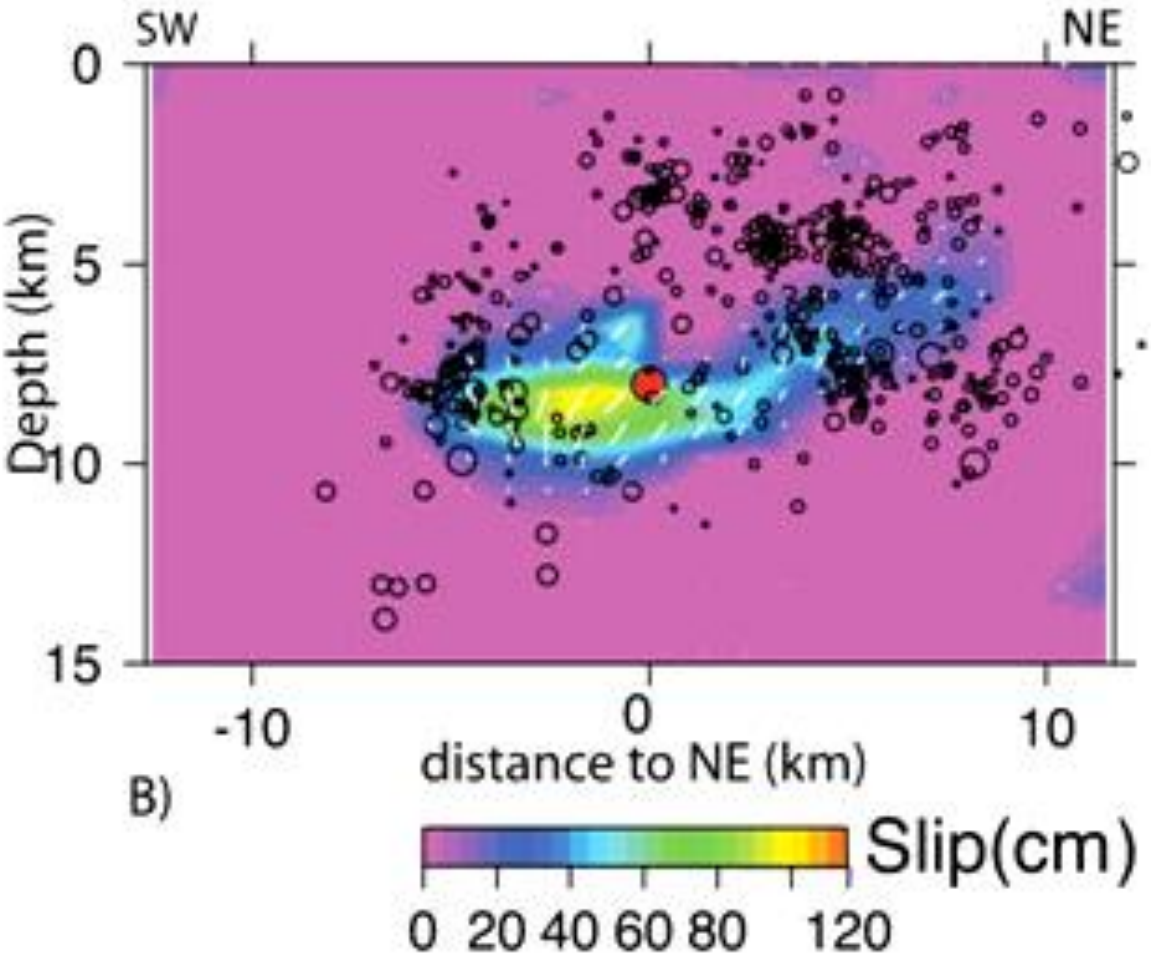

Figure 17. Dreger and others' (this volume) preferred model of offset of the fault plane during the earthquake, and the aftershocks projected onto the Wells earthquake fault plane. The hypocenter is the red circle. This earthquake model generates the red waveforms seen in figure 16. This model of earthquake slip could be substituted for the Wells earthquake fault plane shown in figure 14.

Faults that are mapped in the Snake Mountains and extend underneath the sediments of the valleys may have had a role in influencing the Wells earthquake source and aftershocks (Thorman and Brooks, this volume). Thorman and Brooks note that the hypocenter of the event is where the Oxley Peak fault would intersect the Wells earthquake fault. Other potential structural relationships are the intersection of the Wells earthquake fault with the Cedar Peak fault zone as the possible northern boundary of the earthquake rupture, and the intersection with the southern boundary of the Wells fault being near the southern limit of the early aftershocks (Thorman and Brooks, this volume). A crudely layered geology and subhorizontal structures in the upper crust (e.g., figure 2 of Henry and Colgan, this volume) may have arrested the upward propagation of the rupture and led to its blind nature. In particular, there is a large, subhorizontal mylonitic shear zone at about 2 to 3 km (1.2 to 1.9 mi) depth that may have served as a relatively weaker area to penetrate (figure 2 of Henry and Colgan).

The earthquake occurred directly below the sedimentary basin of Town Creek Flat, which likely trapped seismic waves making the duration of shaking longer and potentially made some wave amplitudes larger. Computer simulations of the earthquake waves by Louie (this volume) show trapped wave energy in Town Creek Flat continuing after the shaking in the bedrock has calmed down (figure 18) and indicate that a much larger sedimentary basin to the west, the Marys River basin (Ponce and others, this volume), also traps seismic waves and sends some of these waves back towards Wells, potentially further extending the duration of shaking at Wells. This would help explain the long duration of shaking of 40 seconds that was reported by the citizens of Wells and observed on surveillance cameras.

The earthquake was felt throughout Nevada, in eastern Utah (including at Salt Lake City), and in southern Idaho (figure 19).

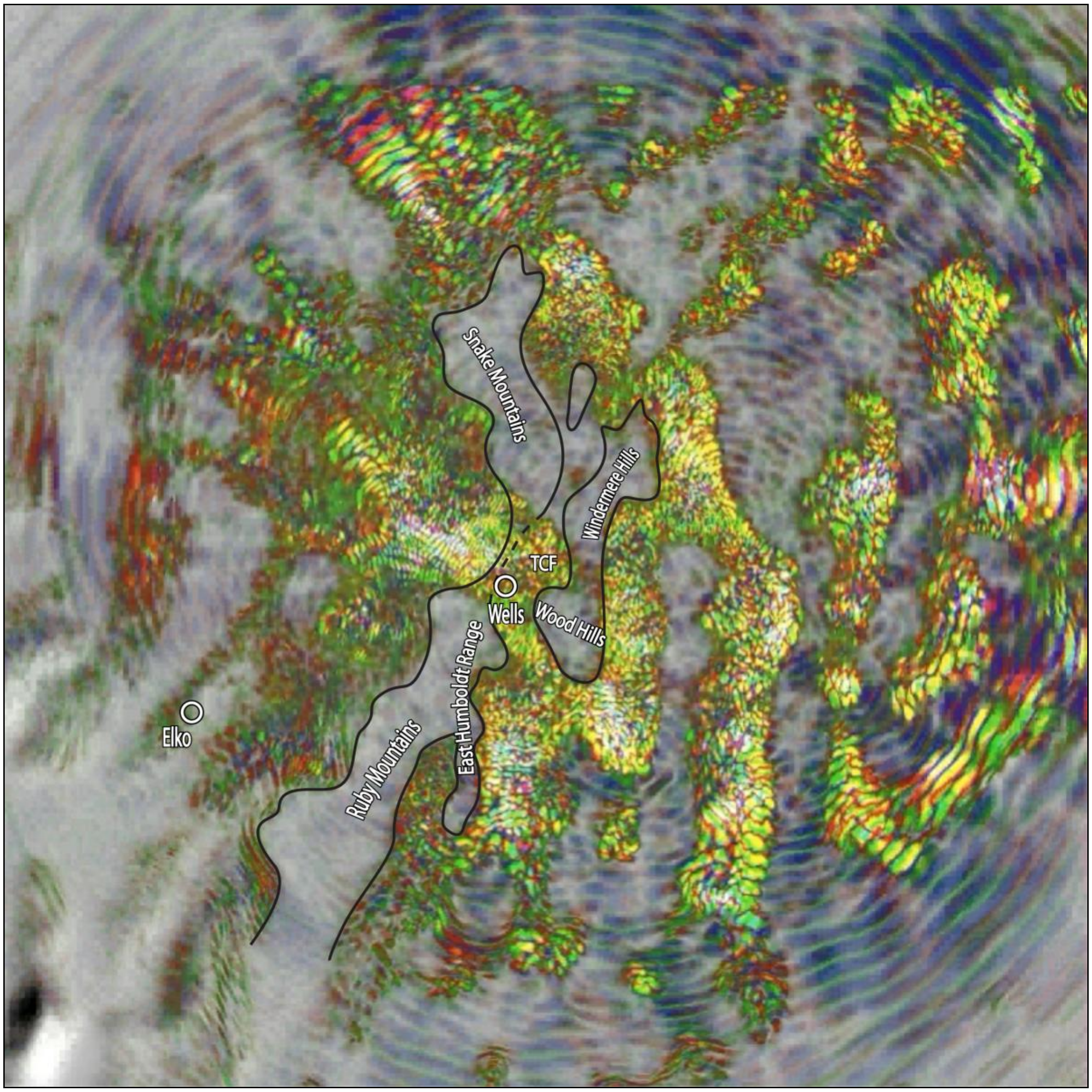

Figure 18. Frame from a preliminary simulation of the 2008 Wells earthquake by Louie (this volume). The earthquake epicenter is at the center of the figure. Wells is shown. Some of the ranges around Wells are also roughly outlined and labeled. Town Creek Flat is labeled "TCF". The colored areas in the image are where the shaking is stronger and the gray areas are where there is less shaking, or shaking has stopped. The frame is frozen when the shaking in the bedrock, or mountains, around Wells has calmed down and large surface waves are seen moving out at the edges of the frame, approximately 54 seconds after the mainshock begins. Note, however, that Town Creek Flat and Wells are still shaking because of seismic waves trapped in the sedimentary basins. Similarly, other sedimentary basins in the region can be seen reverberating from the earthquake as well. The patterns of shaking in this figure are a major clue as to how large earthquakes in the Basin and Range Province will manifest themselves.

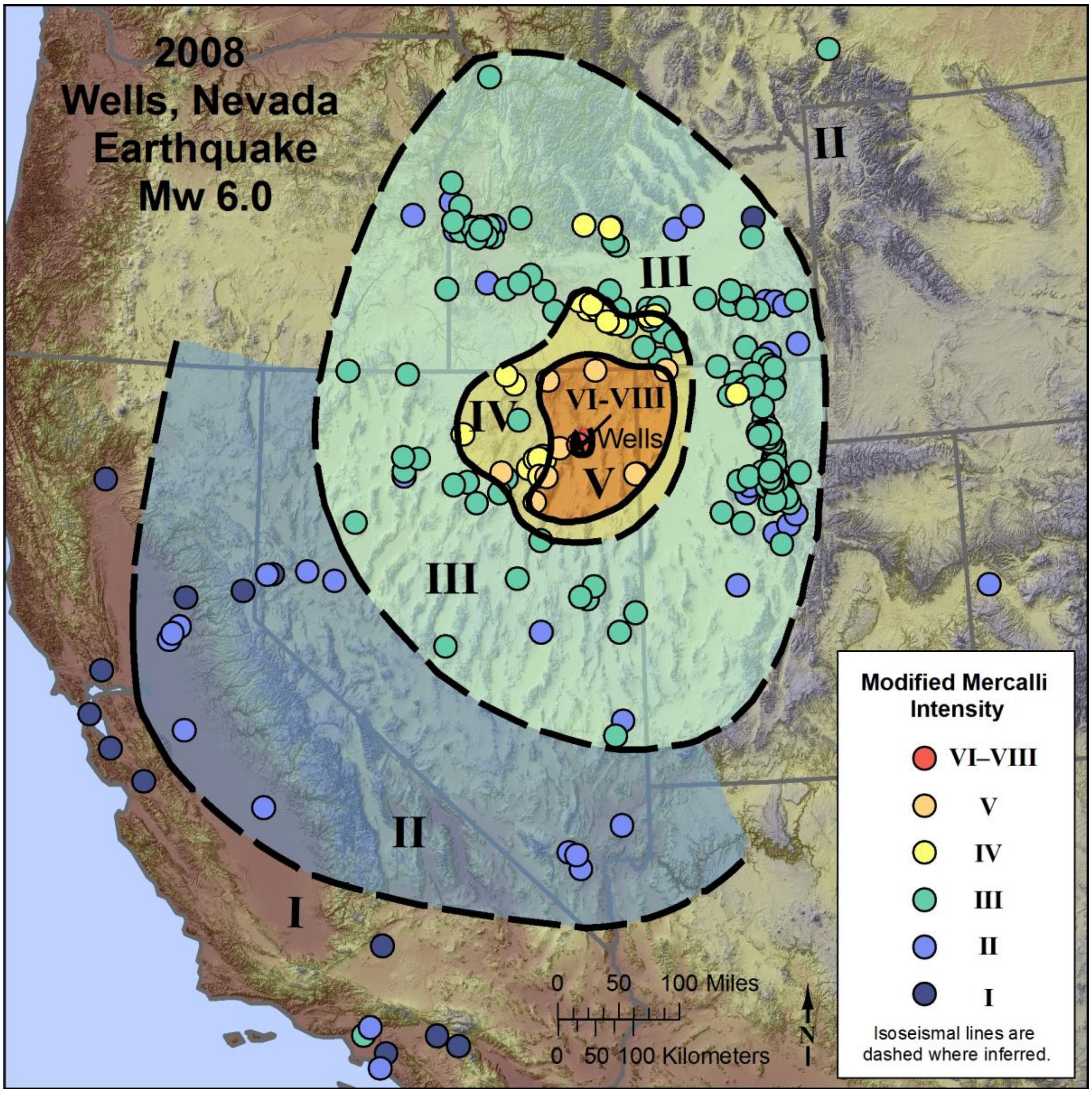

Figure 19. A Modified Mercalli Intensity map of the 2008 Wells earthquake produced by dePolo and Pecoraro (this volume). The highest intensity shaking that was damaging (VI to VIII) was confined to the area around Wells. The areas that strongly felt the earthquake (VI-V) were confined to northeastern Nevada and adjacent parts of Utah and Idaho. The earthquake was distinctly felt in Salt Lake City and was felt as far away as Las Vegas. The primary data used for this map were the U.S. Geological Survey "Did-You-Feel-It" survey results.

THE IMPORTANCE OF UNDERSTANDING THE WELLS EARTHQUAKE

Earthquakes provide a natural, full-scale laboratory for learning how to make buildings that can withstand strong shaking, how a community can best respond and recover from a disastrous event, and how to better characterize earthquake sources. The emergency response and recovery from the Wells event benefited from similar studies that had been conducted on previous earthquakes where lessons learned were published and incorporated into model emergency response plans, incident command system models, building codes, training, and so forth. The 2008 Wells, Nevada earthquake is important to document, study, and understand for the following reasons:

- It caused damage and disruption to a Nevada community.
- It occurred in a relatively lower seismic hazard part of the state, which underscores that earthquakes can happen anywhere in Nevada.

- It was a damaging background earthquake without surface rupture and occurred on a previously unmapped fault strand, which was possibly undetectable prior to the earthquake.
- It was an example of a typical, Basin and Range Province normal dip-slip event.
- It was the largest earthquake to occur within Nevada in the last 42 years, the largest event in the Basin and Range Province within the last 15 years, and was the largest earthquake to occur in the contiguous United States in 2008.
- It was a well-recorded earthquake that occurred within the EarthScope USArray seismograph station deployment in Nevada and surrounding states, and the local area was rapidly instrumented with portable seismometers.
- It occurred beneath a sedimentary basin, a common setting for western communities, and there were many aftershocks recorded on seismometers in and outside of the basin that can be used to understand basin response.
- It affected a rural community that successfully survived the event with no deaths, three minor injuries, and only one business failure.
- The effective emergency response is a model for rural communities.
- The effective recovery is a model for communities in general.
- The effective social response and the behavior of the affected people are a model for dealing with earthquakes and earthquake disasters.
- The damaged and undamaged buildings support the importance of using the seismic provisions of building codes and illustrate the poor performance of unreinforced masonry buildings during earthquakes.

The tectonic region where Wells is located is known as the Basin and Range Province, after its alternating mountain-and-valley topography. The most common earthquake faults in this province are normal dip-slip faults (extensional faults where the two sides pull away from each other and one side slides down) and strike-slip faults (where the two sides slide horizontally by each other). The Wells earthquake was a normal dip-slip earthquake. This event was well recorded on modern instrumentation (e.g., figure 20) and analyzing data from the Wells earthquake will help us further understand the shaking hazard posed by normal faults and how seismic waves can be trapped and enhanced by sedimentary basins, such as Town Creek Flat.

Figure 20. Temporary seismic array station with transmission antennas installed to record aftershocks from the Wells earthquake. These stations are used to precisely locate the aftershocks and also to provide the characteristics of ground motion at the site.

We have attempted to document the earthquake's impact on the rural community of Wells and the effectiveness of the response and recovery, with a focus on what was successful and what could be improved. Wells, Nevada is a typical rural community, albeit a fairly progressive one. They have emergency response resources and training, but it is limited to the scale of the community and there are significant distances (80 km, 50 mi) to the nearest additional resources. There has been a natural focus on responding to and recovering from high-risk urban earthquake catastrophes. State representatives have been concerned with whether enough attention has been paid to understanding the scope, setting, and appropriate response for a rural earthquake disaster, however. With a far greater number of rural than urban communities scattered throughout Nevada and the west, it is more likely that a rural community will be affected by the next damaging earthquake as was illustrated by the 2008 Wells event. Although there were distinct hardships associated with this earthquake, the community, region, and state handled these issues such that critical incidents were limited to their original extent, resources were managed in a way to limit business failure, and the community engaged rapidly and effectively in recovery. Over $6 million of relief funding was available to assist with a >$10.5 million event, greatly facilitating recovery.

Wells was progressive in ways that helped it survive this earthquake and its aftermath. It had an emergency response plan, it followed the incident command system, emergency personnel were familiar with each other and had worked together on emergency responses before, it used building codes with seismic provisions, the city and school district had earthquake insurance on their buildings (several of which were damaged by the earthquake), and the pioneering attitude of people was conducive to dealing with the disaster in an effective manner. This attitude was partly manifested as strong, positive leadership in the community. These are all clues to how rural communities can survive a disaster well, but there are many lessons here for urban communities as well.

With any disaster comes the opportunity to learn from it and minimize the impact of any subsequent disaster. This is the only way that cycles of damage and misfortune from earthquakes can be broken. Wells benefited from past disasters, such as having adopted model emergency plans and some building codes, and having purchased insurance specific to earthquakes on some buildings. Since the earthquake, they now have purchased an emergency radio system and have been organizing citizen response teams to enhance some of the weaker parts of the earthquake response. Many of the buildings damaged by the earthquake in Wells have been fixed and made stronger, including the high school gym, the high school auditorium, and a church, all of which host large gatherings of people at times; now those gatherings will be safer from any future earthquakes (figure 21). City Hall and the city shop are being moved out of unreinforced masonry buildings into new, seismically resistant buildings, helping to protect the city employees from future earthquakes and assure the functionality of these buildings in a post-earthquake environment. The people of Wells witnessed great compassion and generosity from each other, from the local businesses, and from surrounding communities. This made dealing with the losses and cleaning up the mess a little easier. We can garner the lessons learned from the earthquake and encourage the implementation of these in other communities, but it needs to be emphasized that the real key to the successful emergency response and recovery lies in the people involved, their attitudes, and their training, including the hundreds of volunteers who were not directly affected but came to help the community. This may seem like an abstract lesson that can't be taught, but it is a critical factor that should not be taken for granted and can be taught before, during, and after a disaster though public messages, personal eye-witness experience examples, and good leadership.

Background earthquakes that don't rupture the ground surface can occur along mapped, unmapped, blind, buried, and unrecognizable faults throughout Nevada. They are events with magnitudes of 6.5 and smaller, but as the 2008 earthquake shows, they can be damaging and disruptive to communities when they occur close to populated areas. The Wells earthquake underscores the importance of considering background events in seismic hazard characterization.

Nevada is earthquake country with a moderate to high seismic hazard throughout the state. This earthquake occurred in one of the relatively lower hazard parts of the state, however, rather than in an area with high earthquake probability. Although poorly instrumented with seismometers, northeastern Nevada has fewer recorded earthquakes than the western half of Nevada (figure 1) and has a lower amount of geodetic strain measured (c.f., Hammond and others, this volume; Petersen and others, this volume). A 2009 earthquake probability calculation based on the U.S. Geological Survey National Seismic Hazard Map dataset (http://earthquake.usgs.gov/hazmaps/; Petersen and others, 2008) indicates that the chance of having an earthquake of magnitude 6 or larger within 50 km (31 mi) of Wells over 50 years is 10% to 12% (figure 22). These are small percentage chances (1 in 10), yet an earthquake did occur, nucleated within 9 km of town, and damaged the community. The occurrence of the Wells earthquake in northeastern Nevada emphasizes that damaging earthquakes can occur anywhere in the Nevada, and all of Nevada should be prepared for strong shaking. The chances for the same or larger magnitude event occurring within 50 km of Reno and Carson City over a 50 year period are 60% to 65%, and the probabilities for an earthquake occurring within 50 km of Las Vegas are the same as for Wells over a 50-year period, 10% to 12%. The 2008 earthquake cautions us against discounting the earthquake risk just because a probability calculation generates a low value. Society has to be smarter than that and commit to surviving low probability–high consequence events, such as earthquakes, without major hardships and disruptions to a community. This requires a community to engage in earthquake preparedness; earthquake mitigation for safety and value; earthquake response planning and training; and earthquake recovery planning. Fortunately there are many resources available to assist communities in preparing efficiently, and many have begun to do so.

Figure 21. Reconstruction of the Wells High School gymnasium. This will be a safer building for the high occupancy the gym occasionally has during any future earthquakes.

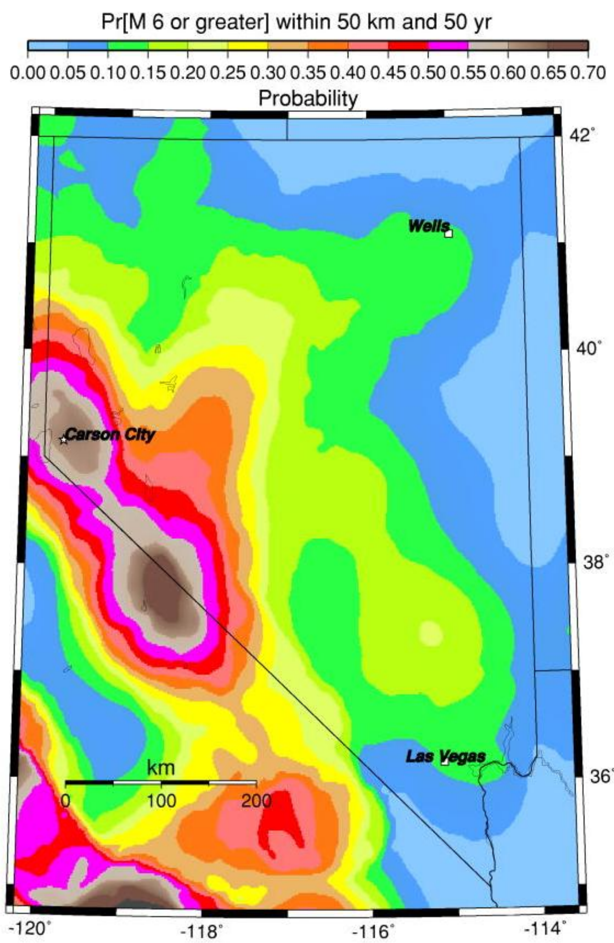

Figure 22. The probability of a magnitude-6-or-greater earthquake occurring within 50 km (31 mi) and within 50 years of any location in Nevada and parts of surrounding states, including a portion of the San Andreas fault zone in the lower left corner. The map is based on data from the U.S. Geological Survey National Earthquake Hazard Map database, and the probability calculator can be found at http://earthquake.usgs.gov/hazmaps/. *Figure is courtesy of Stephen Harmsen, U.S. Geological Survey*.

FACTORS CONTRIBUTING TO BUILDING DAMAGE FROM THE EARTHQUAKE

Several factors appear to have potentially contributed to the building damage from the Wells earthquake and can be categorized into two groups: those factors related to ground motion aspects and those factors related to building type and condition. Preparing for and mitigating these factors are effective strategies for reducing earthquake losses. Furthermore, earthquake planning scenarios that consider these factors will be realistic. Factors that contributed to damage from the Wells earthquake include the following:

Ground Motion Factors

- proximity of the earthquake to Wells
- possible high-stress drop source effects
- possible earthquake rupture directivity effects
- sedimentary basin effects
- sedimentary basin-edge effects
- a long duration of shaking
- low average shear-wave velocity site conditions

Building Type and Condition Factors

- unreinforced masonry buildings
- lack of seismic detailing
- poor construction practices
- poor building materials
- poor building condition and maintenance
- second-story effects
- proximity to a damaged building

The proximity of the earthquake to Wells was a major factor in damage. Had the earthquake been two or three times more distant from Wells, damage would have likely been much less severe. The Wells earthquake was recorded at distances of 37 km and greater. Ground motions were about at expected values for the size and distance from the earthquake out to about 200 km and farther distances, where they fell a little below expected values (Petersen and others, this volume). Nevertheless, a number of models for the mainshock give results that had moderately high stress drops (89 bars in Smith and others, this volume, and 72 bars in Mendoza and Hartzell, this volume) for normal fault earthquakes (c.f., Becker and Abrahamson, 1997); high stress drops have been related to high-frequency strong ground motions (c.f., Hanks, 1979), so damaging high-stress drop-source effects from the Wells earthquake cannot be ruled out. Dreger and others (this volume) noted that although "the rupture was bilateral, the greatest slip is located southwest of the hypocenter resulting in directivity amplification." Thus, wave directivity effects may have enhanced ground motions in potentially damaging ways.

The characteristics of sedimentary basins, such as the relative location, size, and shape of the basin can trap, focus, and amplify seismic waves (c.f., Anderson, 2003; Kawase, 2003). The Town Creek Flat sedimentary basin was directly over the earthquake and is about 1.8 km, or a little over a mile, deep near where the epicenter is located. Wells is located on the edge of this basin, which thickens to the north and northeast, and thins to the south of town (figure 23). The 40-second duration of shaking that was widely reported in Wells and can be seen on security camera footage is much longer that would be typical for a magnitude 6 earthquake (c.f., dePolo and others, 2010); this was likely caused by waves trapped and reverberating in the local basin, and possibly by waves trapped in an adjacent, much deeper and larger sedimentary basin to the northwest, the Marys River basin (figure 23; Ponce and others, this volume; Louie, this volume).

An important study in this documentation effort was the measurement of the average shear-wave velocities of the upper 30 m (100 ft) of deposits, called V_s30 m, in areas that were damaged by the earthquake. These measurements are important because they have been found to correlate with damaging ground motion (c.f., Anderson and others, 1996). These average shear-wave velocities can be used by the City of Wells to engage in the latest versions of the International Building Code, which use them to characterize the amount of earthquake resistance that is needed for life safety in buildings. Refraction Microtremor (ReMi) techniques were used to measure average shear-wave velocities by recording seismic waves created by passing trains and from cars and trucks on the freeway (O'Donnell and others, this volume). The measurements indicate V_s30 m shear-wave velocities that are all in the International Building Code National Earthquake

Hazard Reduction Program Site Class D, one of the lower velocity classes. Average V_s30 velocities of 297 to 303 m/s (973 to 994 ft/s) were measured in areas of major building damage from the Wells earthquake. The ReMi modeling produces a subsurface velocity profile that shows potential velocity changes at depth. At some sites, possible wave-trapping high-velocity layers and velocity inversions below may have further influenced ground motion. An example of the analysis by O'Donnell and others from the damaged Wells historical district is shown in figure 24.

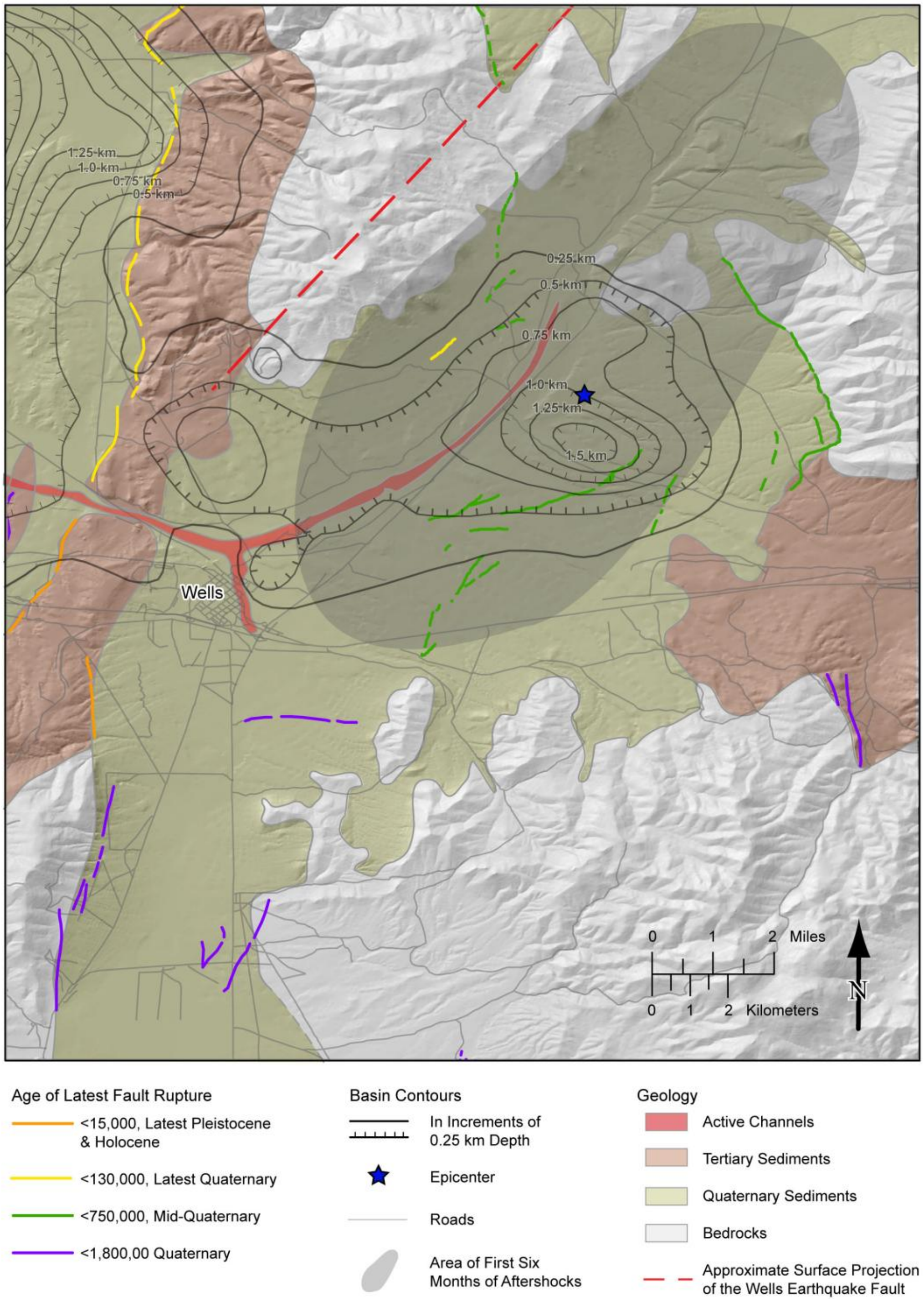

Figure 23. Quaternary faults, general geology, basin depths, and the epicenter, aftershock area, and surface projection of the 2008 Wells earthquake. The geology is simplified from Henry and Thorman's map (this volume); the basin depths are from modeling of gravity data by Ponce and others (this volume) and Ponce, 2011, written communication; the earthquake epicenter, aftershock area, and surface projection are from Smith and others (this volume). The Quaternary faults are from the U.S. Geological Survey (2006) and dePolo (2008). Note that Wells is near the edge of the structural basin that forms Town Creek Flat.

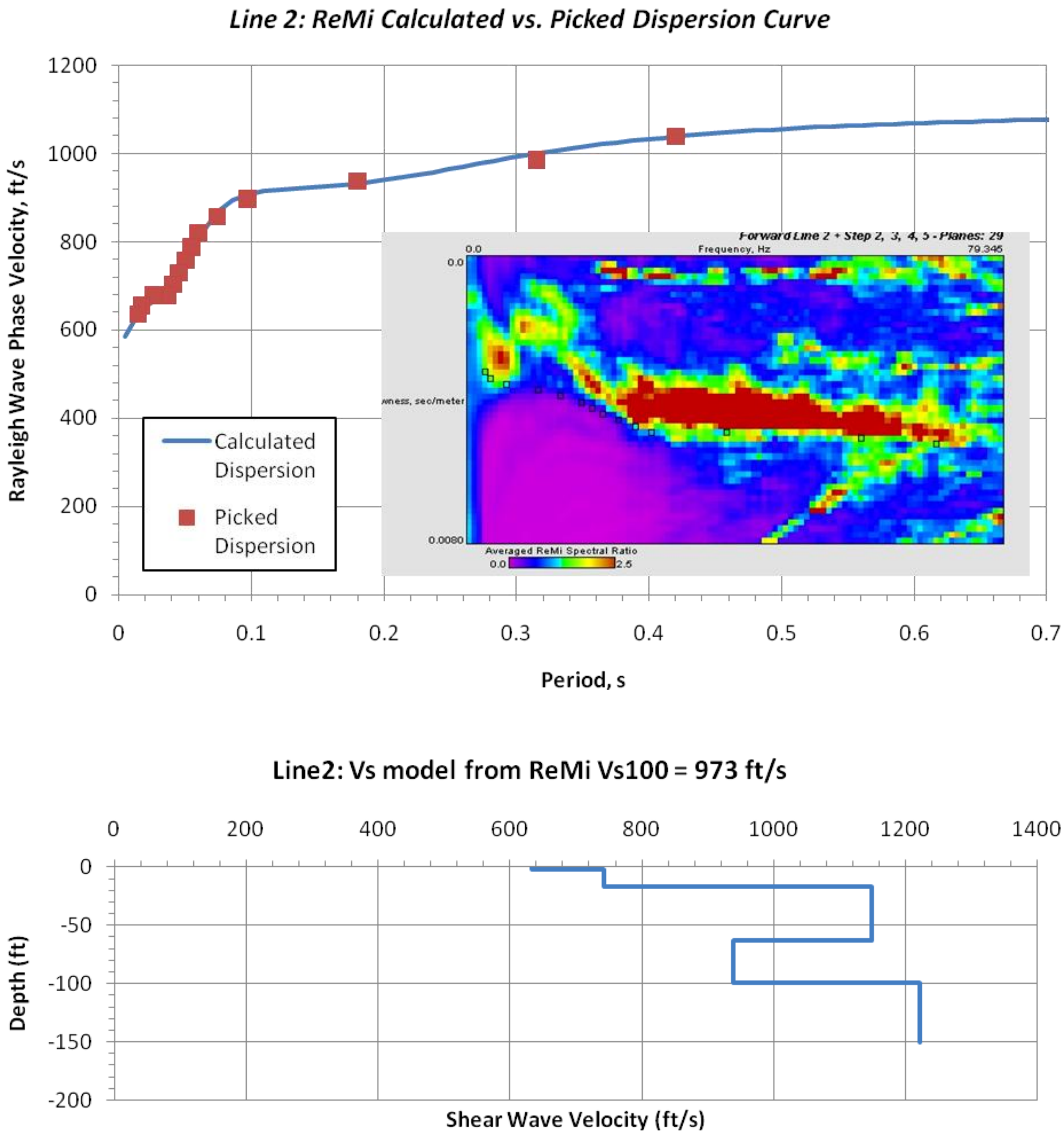

Figure 24. Wells Refraction Microtremor Line 2 model of the soils in the damaged Wells historical district from the study by O'Donnell and others (this volume). The noise from passing trains and cars is transformed into the colorful inset figure, a slowness-frequency diagram (slowness is 1/velocity). The minimum edge picks (hollow black squares) are shown in the upper Rayleigh Wave Dispersion Curve graph (red squares). The lower graph shows the preferred shear-wave velocity with depth model that is used to calculate the dispersion curve in the upper graph (the solid blue line). The best or simplest fitting curve is considered the preferred curve and is used to calculate the average shear-wave velocity for the upper 30 m (100 ft).

Unreinforced masonry buildings are notorious for being damaged from earthquakes (e.g., Steinbrugge, 1982; FEMA, 2010). They lack the lateral strength required to withstand earthquakes, can generate high inertial forces during earthquakes, have inherent weaknesses (such as cracking with time and deteriorated mortar), and are made up of components that are very damaging and dangerous when they fall, such as bricks and crowning concrete bond beams (figure 25). There was no consideration given to seismic detailing in the construction of these buildings, such as anchoring parapets. In addition, many poor construction practices were evident in the damage. These included lack of cross-tying of brick courses together (header courses), rubble infill walls, unlaid bricks in the central parts of walls, lack of mortar between bricks–particularly along vertical faces, and only partially filled concrete block columns that should have been completely filled to support the weight of ceiling beams. Poor building materials were also observed in damaged buildings, such as unfired bricks and rocks with rounded edges thrown in the rubble infilling of walls (figure 26). The maintenance and condition of the buildings also seemed to be a factor. Prior to the earthquake, some buildings had been unoccupied for decades, were not maintained, and had developed weakened parts, such as mortar between bricks that had been eroded away and partially collapsed areas.

Figure 25. The roof of the unreinforced masonry San Marin Hotel lies on top of the second story floor and the collapsed and disintegrated two-story western wall.

Two-story buildings appeared to have been the most extensively damaged, although the specific reason as to why this was the case has not been identified yet. Possible reasons include greater drift of second stories, potential resonance with longer-period ground motion, and potential buttressing effects from adjacent one-story buildings. Structures next to damaged buildings commonly received damage debris from these adjacent buildings causing roof damage and potentially the partial collapse of one structure.

These potential damage factors are important, but the exact magnitude of their importance in influencing damage is unknown at this time; hopefully future research will identify which of these were the main damage factors. The recognition of these potential damage factors is important as they have potential application in seismic hazard risk reduction and in creating more realistic earthquake scenarios for emergency planning purposes.

Figure 26. A damaged wall exposed a rubble infill of broken bricks and rocks with intermittent mortar dumped in, all hidden behind a single thickness of laid brick wall. This kind of construction offers an uncertain performance during an earthquake.

THE 21 FEBRUARY 2008 M_W 6.0 WELLS, NEVADA EARTHQUAKE

This volume is a description of the earthquake and its impacts from several different points of view with the goal of extracting lessons that can be applied elsewhere to minimize future impacts and help communities successfully recover from future earthquakes. The volume is arranged into eight sections:

I. **Summary**
II. **Introduction**
III. **Geologic and Geophysical Setting**
IV. **Seismic and Infrasound Studies**
V. **Geodetic and State-of-Stress Studies**
VI. **Earthquake Damage and Effects**
VII. **Response to the Earthquake, Community Impacts, and Disaster Recovery**
VIII. **Lessons Learned**

Appendices include a geologic map of the Wells earthquake area, a satellite InSAR image of the deformation from the earthquake, a photographic library of pictures related to the earthquake, and PowerPoint presentations for educators. Many of the papers are elaborations of work that was initially posted at the virtual earthquake clearinghouse site (figure 27) that was set up immediately following the event for the prompt exchange of information on the earthquake as soon as it became available.

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The scientists who came to Wells or otherwise engaged in the event and all those who aided them deserve thanks for their contributions to the documentation and understanding of this earthquake. Three groups provided assistance with Sno-Cats and the deployment of the portable seismometers: the Nevada Department of Transportation, Wells Rural Electric, and the Elko County Sheriff's Department. Communication links for the data streams was provided by Nevada Department of Information Technology.

Special thanks are given to the individuals who helped make this volume a reality. Directors Jon Price of the Nevada Bureau of Mines and Geology and John Anderson of the Nevada Seismological help set the foundation of the volume and supported its development. Cartographic drafting of figures, typesetting, and assembling the volume was provided by Jennifer Mauldin, Jack Hursh, Matthew Richardson, and Irene Seelye, all from Nevada Bureau of Mines and Geology. Wonderful cartographic efforts were made by Yui Miyata from the Nevada Seismological Laboratory for important public web postings in the months following the earthquake. These cartographic efforts are critical to the communicative success of the volume and in communicating earthquake information to the public. D.D. LaPointe of the Nevada Bureau of Mines and Geology edited hundreds of pages for this volume making it read smoother and more accurately. Many reviewers went through the papers making sure the science was sound and helping to spot missing language which enhanced the text; they are commonly acknowledged at the end of each paper, and were greatly appreciated by the Bureau.

This volume is dedicated to the people of Wells and Elko County and the many companies, agencies, and people that helped in the response, recovery, and scientific efforts related to this earthquake. Many individuals were inspiring and taught us with their abilities and wherewithal how to effectively respond to an earthquake. The citizens of Wells graciously allowed us to document their disaster for the benefit of all communities, and deserve collective thanks.

CONVERTING METRIC UNITS TO ENGLISH UNITS

With the exception of one paper, all units are given in metric units, the standard units used in science. The conversion of metric units to English units is easy if you have a calculator. Multiply the metric unit by the conversion value to get the English unit value.

Conversion Factors:

1 centimeter = 0.394 inches
1 meter = 3.281 feet
1 kilometer = 0.621 miles

For example, if you want to convert the statement "it was 9 km away" to miles, multiply "9" by 0.621 to get 5.6 miles.

Figure 27. Upper part of the Nevada Bureau of Mines and Geology Wells Technical Clearinghouse page that, along with the earthquake page of the Nevada Seismological Laboratory, posted the first reports on the earthquake and its effects.

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