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Summary of the 2008 Wells, Nevada Earthquake Documentation Volume

by

Craig M. dePolo[1], Kenneth D. Smith[2], and Christopher D. Henry[1]
[1]Nevada Bureau of Mines and Geology, [2]Nevada Seismological Laboratory
University of Nevada, Reno

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INTRODUCTION

On February 21 at 6:16 a.m. PST, northeastern Nevada was struck by a moment magnitude (M_w) 6.0 earthquake, the largest event in Nevada within the last 42 years, the largest earthquake to occur in the Basin and Range Province in the last 15 years, and the largest earthquake to occur in the conterminous United States in 2008. With support from the U.S. Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), the University of Nevada, Reno, the Nevada Earthquake Safety Council, the Nevada Division of Emergency Management, the Nevada Seismological Laboratory, and the Nevada Bureau of Mines and Geology, a collection of papers has been put together on the 2008 Wells earthquake to document the event. Twenty-eight papers are included along with a geologic map of the region surrounding the earthquake fault, a satellite interferometric synthetic aperture radar (InSAR) image that shows ground displacement resulting from the earthquake, PowerPoint presentations, and hundreds of photographs of earthquake effects.

The volume covers not only the many scientific aspects of the earthquake such as the geological, geophysical, seismological, and geodetic settings but also the community impact aspects of the earthquake: damage to buildings, houses, and utilities; the emergency response; community recovery; and impact on city government. These papers are further enhanced by numerous photographs and images, and a video made by a local community member. The goal of the volume is to document as many important aspects and lessons of the Wells earthquake as possible, so these can be used by Wells and other towns and cities to better prepare for earthquakes and to design more earthquake-resilient communities. Earthquakes are inevitable in Nevada, but injury, damage, and loss from earthquakes can be greatly minimized with some forethought and preparation. This volume gives insight into the effects of a major earthquake on a Nevada community to aid in these endeavors.

LESSONS LEARNED

Lessons learned from the 2008 Wells earthquake are documented and discussed in detail in the papers of this volume, but a white paper by the Nevada Earthquake Safety Council summarizes several major conclusions about the Wells earthquake, in a listing of "lessons learned" from the Wells earthquake that apply not only to Nevadans but to all residents of earthquake-prone areas. They cover basic earthquake preparedness, a strategy for lowering the number of calls to the emergency 911 system ("check on your neighbors"), continued warnings about the seismic vulnerability of unreinforced masonry buildings, enhancements for emergency response and recovery, and an appeal for increased earthquake monitoring capability and Quaternary fault studies in the state to accurately and more completely define the earthquake hazard. The Council's lessons learned are as follows:

Lessons for Nevadans:

- Earthquakes can occur anywhere in Nevada.
- Nevadans need to know what to do if there is a strong earthquake.
- Nevadans should secure, relocate, or remove dangerous items that can fall on people and hurt them.
- If you are inside a building during an earthquake, stay inside; if you are outside, get away from buildings.

- Volunteers are essential to the success of the response and recovery.
- After a strong earthquake occurs, check on your neighbors.

Lessons about Buildings:

- Seismic provisions in modern building codes are important to use in Nevada.
- Unreinforced masonry buildings and unanchored masonry veneers are extremely vulnerable to earthquake damage and failure.
- Balconies and sidewalk coverings may be able to be strengthened to provide protection against falling bricks and other debris.
- Crowning bond beams on top of walls are particularly dangerous elements of unreinforced brick buildings during earthquake shaking.
- Buildings that are in severe disrepair, have partially collapsed, or have incomplete structural systems may be subject to total collapse during earthquakes.
- Unreinforced brick and masonry chimneys can collapse during earthquakes, causing injuries and severe damage.
- Earthquake insurance is a wise investment.

Lessons about Utilities:

- Research should be conducted to assure that standard propane tanks in Nevada are adequate to prevent liquid propane leaks from the strongest shaking that can occur in the state.
- A well-maintained electrical system stayed intact throughout and following the earthquake, which helped in numerous ways.

Lessons about Emergency Response to Earthquakes:

- Emergency resource allocations and emergency personnel training contributed to a successful emergency response and should continue throughout the Nevada.
- Communication can be severely hampered during an emergency response if robust, uniform, or otherwise connected communication systems are not used.
- All Nevada communities should have emergency plans that can be used for rapid decision-making and that include redundant Incident Command Post locations.
- A satellite-communication truck may be important for incident command and emergency response communications in rural earthquake disasters.
- A large number of placards for posting the condition of buildings should be stored at multiple locations within each county and should be distributed to earthquake-affected areas within a day.

Lessons about Community Recovery from an Earthquake Disaster:

- Nevada communities should develop plans for recovering from a major earthquake disaster.

Lessons about Earthquake Monitoring in Nevada:

- An adequate statewide seismic monitoring system needs to be completed to rapidly and accurately locate major earthquakes in Nevada.

Lessons for Earthquake Fault Studies in Nevada:

- Quaternary faults should be mapped and studied within 25 miles of each Nevada town to assure earthquake hazards are adequately characterized for these communities.

EARTHQUAKE DAMAGE, LOSSES, AND COSTS

Earthquake damage is portrayed in Modified Mercalli Intensity maps, as economic losses and costs, as summaries of the building damage observed, and in building-by-building detail. Damage consisting of collapsed and partly collapsed buildings in the historical district of Wells was characterized as Modified Mercalli Intensity (MMI) VIII (dePolo and Pecoraro, this volume). In the northern half of Wells, broken and fallen chimneys and widespread nonstructural damage correspond to MMI VII. Three houses were destroyed by the earthquake (out of ~450 houses in the Wells community) and more than 60 chimneys were damaged (approximately 10% to 15% of the total number of chimneys; dePolo (b), this volume). Over half of about 80 commercial and government buildings were damaged, with major damage to 17 of these buildings. Four buildings were totally or partly collapsed. Numerous buildings had damaged or fallen parapets and upper parts of walls, and nearly all had cracked exterior and interior walls from the shaking (dePolo (c), this volume). The three principal factors that contributed to this damage were the following: seismically weak, unreinforced masonry buildings; poor building maintenance; and poor quality building materials and construction. The Wells High School gymnasium and auditorium were among those buildings that were structurally damaged (Trabert, this volume); a concerted effort to restore the buildings within six months and be ready for the following school year was successful, at a cost of ~$2.5 million. Most utilities survived the earthquake without interruption. Earthquake damage to utilities consisted of a broken water main, a small “elephant’s foot” or bulge formed at the base of a large municipal water tank, a large electrical transformer that shifted on its foundation, two residential gas line leaks, and a liquid propane tank leak that created a propane gas cloud (dePolo and Eriksen, this volume).

The 2008 Wells earthquake cost the community of Wells more than $10.571 million (dePolo (d), this volume). This can be further broken down into (1) emergency response costs $300,000, (2) direct damage costs >$7,889,000, (3) nonstructural damage costs >$496,000, (4) content loss cost estimate $275,000, (5) revenue losses and recovery costs $376,000, and (6) other indirect cost estimates >$1,746,000. The amount of relief, earthquake insurance coverage, and disaster funding and loans totaled $6,689,000, $4,835,000 of which was paid out by earthquake insurance. The cost of the earthquake minus the relief, insurance, and disaster funding leaves >$3.9 million of uncompensated loss to the community.

EMERGENCY RESPONSE AND COMMUNITY RECOVERY

The emergency response effort to the earthquake disaster was highly effective. Approximately 100 personnel and 40 pieces of equipment responded, and most arrived on scene within about an hour after the event to assist (dePolo and Lotspeich, this volume). All specific incidents were professionally engaged and mitigated by local emergency responders and Wells citizens, and none escalated into larger incidents. These included a liquid propane leak, two broken residential propane gas pipes, and a small stove fire. Approximately 600 safety inspections were conducted on the day of the earthquake to evaluate the damage status of homes and buildings. Initially the snow was spray-painted to indicate the safety status of a building, but then it snowed more, covering the paint. Colored flagging was used next, followed by the more standard green, yellow, and red safety placards.

The recovery of Wells from the earthquake was mostly completed within about two to three years, although there were still a number of damaged buildings to repair or demolish, many of which were unoccupied before the earthquake and many of which have a historical nature. Businesses reopened quickly because the City of Wells included them on the first groups of re-occupancy inspections, had community dumpsters available so damaged items could be disposed to facilitate the clean-up, and supported rapid reconstruction of partially damaged business buildings. Consequently, only one business failed from the earthquake.

The Wells earthquake caused a significant amount of damage but the community of Wells, with support from Elko County, the State of Nevada, and the Federal Government, was able to strategize and manage the disaster well. There can be different circumstances, however, where staff is limited by the economy or people are new and not yet trained or familiar with disasters. A Community Disaster Recovery Plan that identifies potential issues, solutions, strategies, and resources may be critical to a successful recovery in situations where a community does not have as much background as Wells in emergency preparedness.

SEISMIC HAZARD SETTING

The 2008 Wells earthquake occurred in northeastern Nevada, an area with relatively few recorded historical earthquakes, although the sparse coverage of the regional seismic network may have led to uncertainty or under-recording of seismicity in that region. Anderson (this volume) estimates that earthquakes of M_w 6.0 or larger can be expected with an occurrence rate of ~0.01 per year (or an event every 100 years) over a region of ~10,000 km^2 in northeastern Nevada, based on analysis of recorded historical earthquakes. He concludes that the occurrence of the Wells earthquake, and the fact that it is the only magnitude 6 to occur in northeastern Nevada in over 120 years, is consistent with the rates of smaller earthquakes that have been recorded. Although the likelihood of an event like the Wells earthquake occurring next to a community in this sparsely settled region seems very small, Anderson points out that the results are consistent with USGS National Seismic Hazard Map hazard levels estimated for Wells. An estimate of the probability of a magnitude 6 or greater earthquake occurring within 50 km of Wells over a 50 year timeframe is 10% to 12%, based on the USGS National Seismic Hazard Map database (http://geohazards.usgs.gov/eqprob/2009/index.php). This is one of the lower seismic hazard levels in the state; for example, the same calculation for Reno gives a chance of 60% to 65%. Yet, Wells is where the most recent damaging Nevada earthquake has occurred. This observation underscores that damaging earthquakes can occur anywhere in Nevada, at any time, even when the calculated probability of an earthquake is low.

GEOLOGIC SETTING

The geologic setting of the Wells earthquake is described by Henry and Colgan (this volume) and Thorman and Brooks (this volume); Henry and Thorman (this volume) also produced a 1:48,000 scale geologic map with cross sections of the Wells area. These scientists present a detailed geologic and tectonic history of the region with some structures, such as the "Wells fault" possibly inherited from the Precambrian basement and reactivated several times. Local sedimentary basin and mountain structures of the Basin and Range Province formed from widespread extension that began about 16 million years ago. This extension resulted from slip along dominantly west-dipping faults, which tilted local geologic structures to the east (such as in the Snake Mountains) and created the sedimentary basin that underlies Town Creek Flat, where Wells is located, and Marys River Basin, a much larger and deeper sedimentary basin that lies to the west of Wells. Since that time, several east-dipping normal faults formed and appear to overprint the west-dipping set. Although both fault sets have been active in the Quaternary, the Wells earthquake occurred on one of the east-dipping set. Examples of the east-dipping faults are along the eastern side of the Snake Mountains (the eastern Snake Mountains fault), just northwest of Wells, and along Clover Hill (the Clover Hill fault), just south of Wells.

Quaternary fault scarps around Town Creek Flat that were recognized before the earthquake are on these west-dipping faults, but abundant seismic data (Smith and others, this volume) demonstrate that the normal faulting involved in the Wells earthquake dips to the east. To reconcile this difference, Henry and Colgan suggest that the Wells earthquake occurred on a previously unmapped northern projection of the Clover Hill fault, which is the northernmost of a right-stepping, en-échelon series of east-dipping faults that bound the east side of the Ruby Mountains, East Humboldt Range, and Clover Hill immediately south of Wells. All of these east-dipping faults to the south have geomorphic evidence indicating Quaternary activity. The Wells earthquake occurred in a right step between the range-bounding faults to the south and main part of the eastern Snake Mountains fault to the north (Ramelli and dePolo, this volume). The eastern Snake Mountains fault has been divided into sections, and the earthquake occurred along the distributed Town Creek section. This section of the fault includes a probable Holocene fault in the piedmont, a discontinuous range-bounding fault, and the northern projection of the Clover Hill fault or some other fault strand on which the earthquake occurred.

The Wells fault zone (Thorman, 1970; Thorman and Brooks, this volume) is an approximately west-northwest-trending zone of faults mapped in the local bedrock geology (Thorman and Brooks, this volume; Henry and Thorman, this volume). This fault zone is further delineated by geophysical measurements and modeling (Ponce and others, this volume), and may have structurally controlled some aspects of the Wells earthquake. Thorman and Brooks (this volume) suggest that local fault strands of the Wells fault zone intersect the Wells earthquake fault and may have influenced the location of the hypocenter, the northern side of the 2008 rupture zone, and the southern end of the aftershock zone; the "Wells earthquake fault" is the fault along which the 2008 earthquake occurred. The epicenter lies along the southeastern projection of the surface trace of the Oxley Peak fault, and the earthquake may have nucleated at the intersection of this fault and the Wells earthquake fault. Smith and others (this volume) and Mendoza and Hartzell (this volume) suggest that a central part of the aftershock zone that is generally free of aftershock activity is the rupture area of the mainshock (the stress has been relieved from the earthquake, so there are fewer aftershocks there). The Cedar Peak fault, which also appears to be detectable as a geophysical lineament (Ponce and others, this volume), coincides with the northern side of this aseismic area in the aftershock zone. This fault may have served as a structural complexity that arrested the northern propagation of the earthquake rupture. Near the southern end of the early (six month) aftershock zone is a bend in the northern projection of the Clover Hill fault, a right step between the east-facing range-front faults, and the southern edge of the Town Creek Flat sedimentary basin (Ponce and others, this volume). These are all near the southern margin of the Wells fault zone, just north of the City of Wells (Thorman and Brooks, this volume). Thus, the intersection of the southern margin of the Wells fault with the Wells earthquake fault may have limited the southern extent of the first six months of the aftershock period.

SEARCH FOR EARTHQUAKE SURFACE FRACTURES AND LOCAL QUATERNARY FAULTS

DuRoss and others (this volume) and Ramelli and dePolo (this volume) summarize the search for surface fractures; they found no surface cracking related to faulting from the earthquake, although snow cover at the time of the event precluded detailed exploration, which was completed months later. No evidence for liquefaction was found either, but the ground was frozen from a few centimeters to a couple decimeters depth, which may have helped inhibit liquefaction from surfacing. Ramelli and dePolo (this volume) examined local Quaternary faults and the area of the surface projection of the earthquake. The Wells earthquake fault was not recognized before the earthquake. The well-located aftershocks project to the surface in the Snake Mountains (Smith and others, this volume) in an area of weak geomorphic lineaments and short equivocal scarps (Ramelli and dePolo, this volume). However, no fault had been mapped in this area on the geologic map, and offset of geomorphic surfaces is minimal if at all. The Wells earthquake was likely a “blind” event that did not breach the surface based on seismic source models and field reconnaissance and could be further termed a background earthquake for seismic hazard purposes.

GEOPHYSICAL SETTING

Ponce and others (this volume) use gravity and magnetic data to investigate the geophysical setting of the Wells region. In particular, they document the geometry of the local Town Creek Flat basin adjacent to Wells that may have been important in influencing the amplitude and duration of damaging ground motion. Ponce and others (this volume) show a new depth-to-basement map, mostly based on gravity data that indicate that the sedimentary basin below Town Creek Flat is somewhat rhomboid-shaped and reaches a maximum depth of ~1.8 km to the north of Wells, near the epicenter. Basin depths are about 250 to 500 m around Wells and less than 250 m south of Interstate 80 (Ponce and others, this volume). The earthquake occurred directly below the Town Creek Flat sedimentary basin with the upper extent of rupture propagation terminating below the western side of the basin. Sedimentary basins composed of low velocity deposits can complicate earthquake ground motions, potentially extending the duration of strong shaking (c.f., Anderson, 2003). This may help explain the long duration of shaking, as long as 40 seconds, reported in Wells and observed on security surveillance tapes. Wells is located near the edge of a basin, and this also may have contributed to concentrating seismic energy (c.f., Kawase, 2003). Because so many Nevada communities lie in and around basins, these effects should be further studied with the goal of developing strategies for microzoning for basin-enhanced ground motion.

Six Refraction Microtremor (ReMi) measurements were made at damaged areas in Wells to help gain an understanding of the shallow site conditions (O’Donnell and others, this volume). All locations measured have velocities that put them in International Building Code /National Earthquake Hazard Reduction Program Site Class D. Wells ReMi Lines 2, 3, and 4 were in the Wells historical district and at the Wells High School, all locations that had Modified Mercalli Intensity VII to VIII damage from the earthquake, the greatest observed. The preferred 30-m-depth average shear-wave velocity estimates (V_s30) of ReMi Lines 2, 3, and 4 are remarkably similar, 297 m/s (973 ft/s), 303 m/s (994 ft/s), and 300 m/s (983 ft/s), respectively. Wells ReMi Lines 5 and 6 had the highest V_s30 m measured in Wells, 358 m/s (1174 ft/s) and 319 m/s (1047 ft/s), respectively; these sites had limited but serious damage to buildings that would correlate with Modified Mercalli Intensity VII. Velocity-depth profile models for ReMi measurements in the historical district have a higher velocity layer overlying a velocity inversion that may have had a role in influencing ground motion.

SEISMOLOGICAL ASPECTS OF THE WELLS EARTHQUAKE AND AFTERSHOCKS

The February 21, 2008 Wells earthquake was a well-recorded normal-faulting event with a seismic moment of 1.3 x 10^{18} N-m (1.3 x 10^{25} dyne-cm), corresponding to a M_w 6.0 (USGS CMT; Smith and others, this volume). The mainshock occurred at 14:16:02.62 UTC with an epicenter at 41.1656° N latitude and -114.8772° W longitude. Fortunately, the EarthScope USArray network was operating in Nevada and surrounding states at the time and provided good epicentral control of foreshocks, the mainshock, and early aftershocks. Ultimately, twenty-seven portable seismometers were deployed to the region and allowed detailed aftershock and ground motion studies (Smith and others, this volume). Based on aftershock relocations, Smith and others note that the mainshock had nearly pure normal displacement on a fault striking N40°E and dipping 55° SE. They further note that a roughly 8-km-diameter semi-circular area in the central part of the mainshock fault plane was free of aftershock activity. They interpret this as the area of primary fault rupture and, using a radius of ~4 km, estimate an average displacement for the event of 86 cm and a static stress drop of 89 bars. They also propose that the Wells earthquake potentially occurred along a northern projection of range-bounding normal faults to the south.

Dreger and others (this volume) and Mendoza and Hartzell (this volume) use the seismograms from regional stations, including USArray stations, to develop finite-source models for the Wells earthquake. Dreger and others calculated a moment-tensor solution and a finite-source solution using analyses of waveform data and InSAR data. The results depict a northeast-striking, southeast-dipping fault, similar to that found by Smith and others. Dreger and others developed a finite-fault solution that has localized areas of displacement and energy release on the mainshock fault. The greatest amount of modeled slip, 103 cm, is in an area that lacks aftershocks, and modeling of seismic data indicates that most of the slip during the earthquake was below 4 km depth. Using a kinematic, finite-fault inversion procedure, Mendoza and Hartzell model coseismic slip in an area of 4 x 6 km, with the greatest slip, 88 cm, occurring near the hypocenter, and a stress drop of 72 bars. Their model is a bilateral earthquake source that ruptures the entire fault plane in about two seconds.

GROUND MOTION STUDIES

Petersen and others (this volume) review the seismic hazard for Wells that is indicated on the U.S. Geological Survey National Seismic Hazard Maps (NSHM) and document the ground motions recorded for the 2008 Wells mainshock and an M_w 4.3 aftershock. The NSHM indicate a peak ground acceleration of 0.2 to 0.3 g for Site Class D soils in the Wells region, with a 1-in-2475 chance of being exceeded annually. When this hazard is disaggregated, 50% of the contribution to the ground motion is from background earthquakes, similar to the Wells earthquake. The ground motions for the M_w 6.0 Wells earthquake were recorded only at distances of 37 km and greater. Petersen and others find that regional peak ground motions are generally compatible with expected ground motion curves out to about a 200 km distance. At greater distances, recordings are slightly lower than ground-motion-prediction equations used in the NSHM. These important results help validate existing eastern Nevada seismic hazard estimates and attenuation curves. Near-source ground motions of Wells aftershocks were recorded on the local portable seismic array. One of these aftershocks, a M_w 4.3, was recorded at the Wells Fire Station, which is within 100 m of the area of highest damage levels caused by the mainshock (Modified Mercalli Intensity VIII); the fire station is on a soil site (~297 m/s 30-m-depth shear-wave velocity; O'Donnell and others, this volume) a little less than 10 km from the M_w 4.3 epicenter. Petersen and others report that ground accelerations from the aftershock at the fire station "exceeded 0.2 g and experienced sustained accelerations above 0.1 g for about 5 seconds." Thus, the maximum acceleration from this aftershock was close to the peak ground acceleration predicted by the NSHM for a soil class D site. The mainshock of the Wells earthquake caused severe damage near this location, whereas the aftershock only knocked a few loosened bricks off of a couple of buildings (dePolo – field observation during the aftershock). Therefore, the mainshock likely had higher peak accelerations, greater than 0.2 g, in the historical district.

Dreger and others did preliminary calculations of the maximum peak horizontal ground velocity (PGV) at Wells using their finite-source earthquake model and assuming NEHRP Site Class C soil conditions. They calculate a PGV of 13.5 cm/s at Wells, and their modeled ground motion includes an eastward component of displacement, consistent with some of the westward directions that objects were thrown or slid (dePolo(a), this volume).

EARTHQUAKE SOUND WAVES

Burlacu and others (this volume) recorded sound waves from the Wells earthquake at four infrasonic arrays in Utah and Wyoming at distances between ~160 km and ~470 km. They note that the Wells earthquake provides a good opportunity to advance the understanding of how earthquakes generate infrasound energy (~20 Hz frequency sound). They detected "epicentral infrasound" or sound waves formed in the epicentral area that traveled through the atmosphere to the arrays, and infrasound signals generated by seismic waves in the vicinity of the recording stations.

GEODETIC DEFORMATION AND STATIC STRESS CHANGES FROM THE EARTHQUAKE

Bell (this volume) developed an InSAR image using satellite data taken before and after the M_w 6.0 Wells earthquake. The InSAR image shows a depression that formed over the earthquake rupture, with the ground surface in the central part downwarped as much as 15 cm. Hammond and others (this volume) examined regional Global Positioning System (GPS) data from permanent and campaign GPS sites and estimated coseismic displacements from the Wells earthquake and secular background crustal deformation. The nearest stations were 81 and 84 km away and had estimated displacements of 1.1±0.3 mm and 1.0±0.2 mm, respectively from the earthquake. They found that the magnitude and direction of these and other GPS displacements were in agreement with those predicted from rupture models of the earthquake. Based on longer-term GPS rates, Hammond and others found the region is undergoing "transtension with rates on the order of 1 mm/yr over approximately 250 km." They note that "the azimuth of maximum horizontal crustal extension is consistent with the azimuth of the Wells earthquake coseismic slip vector."

Sevilgen (this volume) calculated changes in static Coulomb stress that were imparted by the Wells earthquake on nearby faults. Sevilgen found the largest Coulomb stress increase (0.2 bars) to be along a possible southern extension of the Wells earthquake fault, the Clover Hill fault, and a 0.1 bar increase on the fault bounding the western side of the Snake Mountains (just northwest of Wells), but found small decreases in Coulomb stresses on other local faults. The eastern Snake Mountains fault had not been mapped when this modeling was done and hence was not modeled by Sevilgen. Sevilgen's modeling indicates that faults to the north and the south of the Wells earthquake, likely including the eastern Snake Mountains fault, experienced stress increases making them slightly closer to failure, or closer to having a future earthquake. Decreases in Coulomb stress of 0.5 bars are modeled on faults that overlap with the Wells earthquake rupture, such as the northernmost Ruby Mountains fault system to the west and the northern part of the Independence Valley fault zone to the east; these sections of faults were moved slightly away from failure.

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