Final Technical Report

USGS Cooperative Agreement for Seismic Network Operations

Title: Western Great Basin Seismic Network Operations

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Authors: Glenn P. Biasi, P.I.

Kenneth D. Smith, Co-PI

University of Nevada Reno

Seismological Laboratory MS-174

Reno, NV 89557

(775) 784-4576, (775) 784-4218

FAX: (775) 784-4165

glenn@seismo.unr.edu, ken@seismo.unr.edu

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Project Web Site: www.seismo.unr.edu

Abstract

This report summarizes seismic monitoring and network operations activities of the Nevada Seismological Laboratory (NSL) of the University of Nevada Reno (UNR) under USGS Cooperative Agreement 07HQAG0015 for the period February 1, 2007 to January 31, 2010. During the reporting period the NSL supported systems operations of the Advanced National Seismic System by providing locations, magnitudes, and related developed products to the USGS and the people of Nevada and California. Real-time data was delivered to four cooperating networks in California, the University of Utah, and the NEIC. Over 29,000 earthquakes were located, 98 of which were of magnitude 3.5 or larger. Capabilities to develop moment tensors, ShakeMaps, and EIDS support were developed or improved during the reporting period. Network performance and operational efficiency for ANSS has greatly benefited from data, facilities and staff shared with the network around Yucca Mountain in southern Nevada, which has been operated by UNR for the Department of Energy. Two notable earthquake sequences occurred during the reporting period. The larger was the M_w 6.0 earthquake on February 21, 2008 near Wells, a small town in northeast Nevada. This earthquake destroyed many of the town's unreinforced masonry buildings, and damaged the high school and many residences. Damages totaled about $10M. Between the Earthscope Transportable Array and portable stations deployed by the University of Utah, UNR, and the USGS, recording and documentation of the event has been more thorough than any previous large normal faulting event in the western U.S. A volume has been prepared by the Nevada Bureau of Mines and Geology with supplemental funds through this Cooperative Agreement documenting the earthquake itself, the geologic context, source models, attenuation and strong ground motion, earthquake preparedness and response, and lessons learned for future responses to events in rural areas. The second significant earthquake in the reporting period presented as a growing swarm of very shallow events beneath the Somersett and Mogul suburban communities of west Reno. From the first felt events on February 28, 2008, the number and the size of the events grew with time, with four M3 events on April 15th, then two M4 events on April 24th, and what would prove to be the mainshock, an M_w 5.0 strike-slip event on April 25th. The hypocenter, at 3.1 km, was so near the surface as to create exceptionally high accelerations at the surface, with two component accelerations above 800 cm/sec^2, and the strongest peak vector of 1164 cm/sec^2 or about 1.19g, at ~3 Hz. Recordings, including a large deployment of single component seismometers are being used to refine velocity and basin models of the Reno area. For both events UNR involved extensive community education and outreach, and scientific engagement in person, in public forums, and venues such as the AGU and SSA Annual Meetings. In the future we look toward improvements in bandwidth and data quality from ARRA funding. On the other hand, the pending termination of the Yucca Mountain network operations raises a real potential for impact to ANSS seismic monitoring in Nevada.

Network Operations and Catalog

UNR operates seismic stations in western and southern Nevada and eastern California (Figure 1). Data are telemetered in real time to the recording center on the campus of the University of Nevada Reno. The network includes dedicated strong motion recorders both in the Las Vegas Valley and the Reno-Carson City urban corridor. Station lists and maps are linked from the Nevada Seismological Laboratory home page at: *http://www.seismo.unr.edu.*

Figure 1 also shows the temporary station coverage improvement afforded by the USArray Transportable Array seismic stations during the reporting period (triangles). The timing of this coverage was fortuitous given the occurrence in northeast Nevada of the M_w 6.0 Wells, Nevada event of February 21, 2008. By mid-2008 these stations had been removed, with only one remaining (near TRC, Figure 1) to contribute to backbone coverage. The large changes in station coverage caused network sensitivity to change significantly in time and space during the reporting period. With the removal of the TA stations and after one year, the remaining portable stations, permanent network coverage has been insufficient to locate numerous felt events in the Wells area.

Figure 2 shows the locations of earthquakes M $\geq$1.0 or larger with eight or more associated phases that occurred during the three-year reporting period. Earthquakes M$\geq$3.5 are shown as circles scaled by magnitude. The totals include 9044 at $1 \leq M \leq 3.5$, 98 events with $M_L \geq 3.5$, and 29,167 total located with magnitudes. The largest earthquake during the reporting period was the M_w 6.0 Wells event.

Seismicity in Figure 2 is show pattern consistent with tectonics and fault activity in the region. Activity along the Mohawk Valley fault (MVF) continued as in previous periods, and included two events of $M_L \geq 3.5$. Activity was also noted generally along the Pyramid Lake fault (PLF). Geologically estimated slip rates of this system are controversial, but in the 1-2 mm/year range. Surface indications of geothermal resources at Pyramid Lake occur near the north edge of the zone of distributed seismicity. Distributed seismicity in the Mina Deflection (MD) corresponds to an eastward shift in the main NW fabric of eastern California and western Nevada. Paleoseismic studies confirm the activity on principal faults of this region, but underestimate net slip rates as compared with geodetic studies. Low apparent levels of seismicity in the Mammoth Lakes/Long Valley Caldera (ML/LVC) are partially an artifact of the fact that the USGS northern California network is responsible for earthquakes in this area.

Figure 2 also includes dense seismicity in southern Nevada. The DOE's Yucca Mountain Project has supported UNR to monitor the region around Yucca Mountain (YM; Figure 2) with a network of digital three-component seismic stations centered on Yucca Mountain. This network provides a completeness level of M -0.3 within ~20 km of Yucca Mountain. The catalog area and area of Project emphasis is the region within 65 km (gray circle). The network is operated, however, with an integrated recording, location, and analysis system. The benefit to ANSS of the Yucca Mountain network is evident particularly in the active seismic region east of Yucca Mountain (Nevada's East-West Seismic Zone which evolves into the IMSB, Intermountain Seismic Belt to the east). UNR operates only one permanent station in this area (a 2-component analog; Figure 1), so primary coverage is being provided by eastern stations of the Yucca Mountain network. Recent work of Kreemer et al. (2010) show 1.1 to 1.8 mm/year of is accommodated in the region, plus an additional amount of extension through the Las Vegas Valley. Thus an important component of monitoring of the seismic risk in Nevada has come as an indirect benefit of Yucca Mountain Project. The Department of Energy has recently filed to withdraw its license request to operate Yucca Mountain and is attempting to terminate the project; unless this coverage is maintained or replaced, UNR's ability to monitor at similar levels of capability in southern and eastern Nevada will be compromised.

Reporting to the ANSS Catalog
Posts to the ANSS catalog were conducted manually for most of the reporting period. To improve timeliness, scripting was developed to harvest reviewed solutions from the database and report them to the ANSS catalog. Reporting to keep the most recent two months current is done twice daily on a cron basis. Updates to earlier months of the catalog are pushed as required.

QDDS and EIDS
We maintained QDDS earthquake parameter delivery throughout the reporting period. Preliminary parametric data delivery via EIDS was developed in early 2007. Significant improvement to EIDS delivery were accomplished in 2009 and EIDS has run in parallel with QDDS since mid-2009.

ShakeMap
ShakeMap v3.2 was installed and operational by the Fall of 2009. Improvements were made in the initiation of ShakeMaps to make them event driven as compared with the cron-based polling system used in previous versions. New controls were installed to reduce the incidence of maps initiated by mislocated regional and teleseismic events. ShakeMaps are forwarded to national ShakeMap pages maintained by the USGS.

Organization and Playback of Earlier Waveform Data
A cooperative effort through the Yucca Mountain Project allowed us to copy contents of archive ½" magnetic tapes from 1984 to 1999 into network disk drives. CUSP-era data (mid-1992 through 1999) were extracted at the time. During this reporting period we have made considerable progress with the pre-CUSP data, completing the waveform extractions from PING format and building the waveform archive. Local, regional, and some teleseismic data were restored from both the Western Great Basin and USGS Southern Nevada analog networks and put in CSS 3.0 format database tables. Phase data for earthquakes in the1984-2009 period are available by following links from the NSL home page.

Network Infrastructure and Improvements

Moment Tensor Solutions
We implemented an interactive moment tensor application for regional earthquakes larger than approximately M 3.5. Moment tensors have been routinely developed since August 2009 (http://www.seismo.unr.edu/, Moment Tensor Solution link). Results compare well with MT solutions from UC Berkeley for events in the CA-NV border region. The system implements the grid search method of Ichinose (2010; http://www.seismo.unr.edu/MOMENT_TENSORS/Gene_Ichinose_mtinv_documentation.pdf) that applies Yuehua Zeng's Greens function technique; GFs are built per event solution. An easy to use front end to the application was developed and tested by Gabe Plank (NSL staff), implementing FISSURES/DHI protocols to retrieve data from any DHI server, including servers at the IRIS DMC and the NCEDC. Input to the script is a distance range to recover qualifying stations and specific DHI servers to access data. Therefore, data can be retrieved from the IRIS BUD server or from the IRIS archive. Instrument response information is acquired from the IRIS DMC and maintained/updated locally for the stations used in a solution. The application can also run directly from the UNR DataScope archive. In principal, regional moment tensors can be determined for any global event where a 1-D velocity model is available. Moment tensors can be remotely computed in earthquake response mode to meet ANSS performance requirements. We anticipate better control on regional moment tensors following ARRA station upgrades in 2010-2011. The application runs independently of the main seismic processing systems, and moment tensor tables are populated in the NSL data archive. We will soon be incorporating moment tensor information in regular EIDS transmissions.

Telemetry and Station Remote Monitoring
A web-based system for the use of mobile devices was developed to improve earthquake response and efficiency of field operations. Technical and professional staff use handheld mobile Internet devices to check on and program radios, dataloggers, routers, and data acquisition processes. Elements of this work were first presented at the ANSS-hosted special session on High Performance Networking in May 2007 in Acapulco. Technical staff have substantially improved the efficiency of maintenance operations, and used it in real time during field deployments in the Wells and Mogul areas. The new system was written up and published in the July-August 2008 Seismological Research Letters (Slater et al., 2008).

Seismic Station Improvements
Equipment from two stations used by the Earthscope Transportable Array (BEK and WCN) was purchased in 2008 to improve broadband recording in western Nevada. The goal in these acquisitions was to improve the bandwidth of seismic recording in support of a local Mw capability. Unfortunately both sensors failed after only a few months of operation, so these stations have experienced significant downtime.

Other station improvements included:

Rebuilding analog stations ADH, CAS, TAH, SCH, ORC, HCK, and GNO.
Replacing FEMA-funded Etna at fire station LV09 in Las Vegas with an RT130.
Adding IP communications at LV07 (former SUMR) and LV09.
Adding LV07 and LV09 to the Las Vegas ShakeMap coverage.

Telemetry and Communications Infrastructure

An FCC auction of portions of the microwave spectrum has affected most of UNR's long-haul communications links. This sale has necessitated the conversion of telemetry infrastructure to an IP-based system including IP-radios, Nevada Department of Information Technology T-1 links, and commercial IP fail-over routing where available. Two of the affected microwave legs are on the Nevada Test Site (NTS) and use the 1.7 GHz government band. These links have primary impact on the NTS area, but some ANSS stations, notably from Death Valley, share receiving facilities. Additionally, these links will be part of a broadband link direct to the Las Vegas area from the Reno data center. Negotiations have begun for some commercial band (2.1 GHz) links, but not all links are covered. As a result some links may remain analog for the foreseeable future. Spectrum relocation work has come with significant demands on the administrative, technical, and support staff, and required innovative interim solutions to maintain data flow as individual link conversions are implemented.

A redundant communications route out of Las Vegas Valley was installed, in part to support Nevada Test Site network stations. Las Vegas area stations formerly relied on commercial Internet but now have an automatic redundant/backup route via a Nevada State T-1 link on NTS. The improved link is a cooperative effort and benefits both the Western Great Basin and Southern Great Basin networks. We have also installed a Motorola Canopy 5.8 GHz backhaul radio on Slide Mountain as IP infrastructure support for the Reno-Carson City urban corridor. Work to complete the telemetry backbone upgrade is ongoing, including some support through ARRA.

Recording center improvements

We have installed significant back-up power capability to our primary data antenna area (4 days). Routing and fiber capability has been checked to the recording area. Reliance on campus network for exports was a known weakness, and responsible in part for an extended loss of export capability. In response to this condition, redundant off-campus Internet connectivity through a reliable local ISP using radio connection and battery backup was implemented. The data flow portion of this new route has been tested at full network data load, and is maintained at a fractional load to ensure connection and ready state. Redundant routing to ANSS clients remains to be implemented.

In the reporting period we also developed an alternative backup power implementation for the primary recording and processing computers of the network. Up to approximately 20 minutes these systems could be supported by a 10 kVA uninterruptible power supply (UPS). In normal usage this system would catch transients and was designed to transition to 25 kVA diesel generator if commercial power remained down. A subtle engineering incompatibility between the UPS and the diesel generator was identified with the help of a UNR power systems engineer. Briefly, the UPS would not synchronize with the diesel generator because of capacity and phase issues, but fortunately the computers would run indefinitely on generator power. Our request for ARRA funds to improve the generator and power infrastructure was declined. Subsequently, however, an alternative strategy was developed and implemented using smaller UPS units and taking advantage of the dual power supplies of most servers in the computer system. Capacity for long-term loss of commercial power is not entirely resolved, however. The recording room air conditioner is not on any backup generator, so the heat load would still be a problem for outages of more than a day or two. Alternative solutions are being explored.

Interactivity with ANSS and Other Partners

Interactivity with ANSS partners has taken many forms.

Real-Time Data Exchange
UNR relays data in real time to ANSS partners in southern California, northern California, Berkeley, and Utah, and to NEIC. UNR stations provide significant coverage for CISN real-time response in eastern California including the Mammoth area. These exchanges are provided by Earthworm and Antelope software. Inter-Connection Agreements for computer information exchange were maintained with the NCSN and NEIC.

Coordination During Exceptional Events
Exceptional events were required for the February 2008 Wells event in northeast Nevada and in April 2008 for the Mogul sequence just west of downtown Reno. During the Wells event, UNR was almost immediately in contact with network personnel of the University of Utah Seismic Stations and the NEIC. Coordination was productive in resolving the mainshock location and for magnitudes of larger aftershocks. The University of Utah, NEIC, and UNR all deployed portable seismic stations with the common goal of recording early aftershocks from this relatively rare Basin and Range normal-faulting earthquake. The Nevada Division of Mines and Geology assisted by providing geologists for field reconnaissance and a concerted focus on gathering perishable field indications of strong ground motions. In the Mogul sequence coordination was maintained with NEIC primarily by telephone

Remote Status Monitoring Using SeisNetWatch
The *SeisNetWatch* software was provided by the USGS to provide regional networks with the capability to query real-time data acquisition systems and to develop summary status information about stations, sensors, data latency, etc. An interface to our Antelope real-time system was developed and web directories configured. ISTI completed the configuration in early 2008. *SeisNetWatch* was subsequently integrated into the national *SeisNetWatch* system maintained by the ANSS.

Nevada Division of Emergency Management
A server was installed at the Nevada Division of Emergency Management in Carson City as part of an effort to improve coordination and integration of seismic information. The server allows NSL to pull in waveforms and parametric information in real-time from

UNR for use by NDEM. Communications were implemented as an independent IP radio link to NSL so as to not rely on commercial or public routing.

Nevada Earthquake Safety Council (NESC)
The NESC (http://www.nbmg.unr.edu/nesc/) brings members of emergency planning, policy, building and code enforcement, geologic, earthquake engineering, and seismic communities together for quarterly meetings and presentations to promote earthquake safety in Nevada. The Nevada Seismological Laboratory has regularly contributed to these forums.

Continuity of Operations and Response Planning
Reliance on campus network for exports has been a known vulnerability for parametric and real-time data exchange. Thus vulnerability resulted an extended loss in 2007 of export capability because of an underground transformer fire that took down power to the south half of the UNR campus. In response to this condition, redundant off-campus Internet connectivity was implemented through a local commercial ISP using radio connection and battery backup. This alternate route was exercised with CISN Menlo Park and Pasadena in late May 2008 in advance of an announced campus power outage. Data were rerouted with only minor configuration efforts on each end. The communications route is maintained at a fractional load to ensure connection and ready state.

Special Events

Two notable earthquake sequences occurred in Nevada during the reporting period.

Wells, Nevada, Mw 6.0, February 21, 2008
The M_w 6.0 normal faulting event in Wells, Nevada, on February 21, 2008 (M_o = 1.30 10^{18} N-m; USGS CMT) was felt over portions of four western states (Figure 3). In terms of costs, this earthquake was the most significant, at roughly $10M in damages, since the central Nevada earthquakes of 1954. Fortunately no one was killed, and only a few minor injuries were associated with the event. The historic portion of Wells (MMI VIII; Figure 4), consisting largely of century-old unreinforced masonry buildings, was virtually destroyed. The high school sustained significant damage and was closed to students for several months while repairs and reinforcements were completed. Fortunately, transportation infrastructure, including Interstate 80 and heavily traveled rail lines through town were not affected

By an accident of timing the USArray Transportable Array was still deployed in Nevada and western Utah, so a large amount of very high quality broadband data was obtained for the event. These data are important because there are relatively few well-recorded normal faulting events of this size anywhere in the world. Unfortunately there were no strong motion instruments in Wells or at any nearby stations.

The mainshock involved nearly pure normal displacement on a N40°E striking 55°SE dipping structure. Aftershocks extended along a ~20 km NE-SW trend. Slip estimates from aftershock relocations at UNR and modeling exercises at other institutions are in general agreement with average displacements of 60 to 90 cm and stress drops of 50 to 90 bars. This rupture orientation and sense of motion are consistent with the geometry and general structure of Town Creek Flats basin, with Wells sitting on the southwest margin of this basin. Sediment thickness in the basin is greatest northeast of downtown Wells, and decreases to ~200 meters beneath town. Because sediment thickness tapers toward town, seismic energy may have been trapped and focused, contributing to relatively high ground motions and a long reported earthquake duration.

In reviewing the seismicity in Town Creek Flats basin since 2000, two M > 3 earthquakes (largest M 3.7; both felt in the town Wells) and sequence of small events occurred near the location of the 2008 mainshock beginning on February 28, 2007, almost one year before the M_w 6.0 earthquake. No surface faulting was associated with the Wells earthquake, but surface displacements consistent with the development of Town Creek basin have been confirmed in InSAR imaging.

The Wells event was also notable for the level of cooperation between affected seismic networks. USGS, UNR, and the UUSS all fielded portable instruments to monitor aftershocks (Figure 5). Eventually, twenty-seven temporary portable stand-alone and telemetered seismographs were deployed in the region and near-source area. UNR implemented IP radio communications for USGS RT-130 portable instruments and integrated the data into its real-time network, so aftershocks could be located in real time and the Wells event catalog could be kept reasonably current. Data was provided in real-time to the IRIS data center and to the USGS. Station WNFS was retained at the USFS station in Wells as a longer-term presence. UNR also cooperated with the Nevada Bureau of Mines and Geology to deploy a real-time telemetered GPS station during Wells aftershock sequence.

UNR led or contributed to several presentations in general public meetings and for schools following the earthquake.

Supplemental funding was made available to assemble a data report for the Wells earthquake and to continue seismic monitoring through the end of January 2009. The data report, summarized in Appendix A, includes papers reporting on structural damage and observable effects, non-structural damage, evidence of strong ground motions, the mainshock source parameters and aftershock activity, and the geodetic and geological contexts for the event. The Nevada Bureau of Mines and Geology is leading this effort.

Mogul, Nevada, Mw 5.0, April 25, 2008

The second sequence started February 28, 2008, beginning with felt report from an M 2.2 earthquake. Activity continued at the rate of several per day, many of them felt, accelerating to tens per day. A temporary PC-based seismic station was installed early in sequence a residence near the epicenter and confirmed the shallow nature of the swarm. Experienced observers (e.g., UNR geoscience faculty) living in the epicentral area reliably recognized earthquakes down to M~1.0. The swarm accelerated in activity and moment release (Figure 6), with four M>3.0 events on April 15th, then two M> 4.0 events on April 24, 2008, then less than 36 hours later, the main M_w=5.0 at 11:40 p.m. local time (4/26/08 06:40 UTC). By the end of August, the swarm had produced over 200 earthquakes with magnitude (M_L) greater than 2.0, a size at which most were easily felt and many were startling to residents. The swarm generated an unusual number of felt events because of the exceptionally shallow hypocenters of much of the seismicity (commonly 2 km, S-P <0.25 s; mainshock = 3.1 km; Figure 7) and because the swarm occurred immediately beneath several west Reno area subdivisions.

The mainshock involved right-lateral strike slip motion of a N30W oriented structure consistent with the aftershock distribution, short period focal mechanisms, and moment tensor solutions. The sequence ultimately extended for nearly 8 km in a NW-SE trend (Figure 8), almost entirely confined to shallow depths (< 6 km). A distinct cluster NE of the main trend of aftershock activity evolved later in the sequence and included an M 3.8 event, the largest earthquake of the late period of the sequence.

Four PASSCAL RAMP stations initially requested for the Wells area were installed in the epicentral area and obtained strong-motion records of the M_w 5.0 mainshock. Component accelerations (Figure 9) exceeded 0.8 g at two stations, and one station recorded a peak horizontal vector acceleration of 1164 cm/sec^2 or 1.19g at a frequency of about 3 Hz. The mean horizontal peak velocity exceeded 12 cm/s at all four local stations, and the peak vector velocity at the strongest observed was 54 cm/s. Ground accelerations for three of the four nearest stations exceeded two-sigma predictions from ground-motion prediction equations. Ground motions are documented in detail by Anderson et al. (BSSA, 2009). Six more PASSCAL portable stations were redeployed from the Wells area after the Mogul mainshock to improve station density in the Mogul epicentral area. Most stations were put on IP radio connections and incorporated into the permanent network processing stream at UNR.

This event caused non-structural and content damage to several hundred homes. The motions in the residential neighborhood near the epicenter were significantly greater than the seismic forces required by the 1985 Uniform Building Code “Zone 3” that was in effect when the Mogul neighborhood was developed, but damage to the wood-frame structures in the neighborhood was minimal. Visually the most dramatic damage was the destruction of an elevated wooden flume used to transport water from the Truckee River to a municipal water facility that serves much of Reno. This damage was caused by a landslide of granite boulders from a steep hillside.

Public demand for information was extremely high, approaching a full-time occupation during the height of the activity. Residents were frightened and not sleeping at night. Many moved out of their homes, sleeping in RV’s (or at least one, to a boat) in their driveways. Some who could left town for a few weeks, and many put their homes up for sale. Aftershock activity continued into August before really slowing down.

During the period of active aftershocks, a network of 80 IRIS PASSCAL single-channel Texan recorders was deployed with the idea of using the swarm as a source for basin characterization and Reno area basin velocity estimation. Siting involved a web-based invitation to the public to host instruments. Response was enthusiastic, with several hundred responses from the public to participate in the experiment. Data have been processed by a team of students and preliminary tomographic inversions of shallow velocity structure have been developed. Results were presented at the December 2008 American Geophysical Union meeting. A public meeting was held at UNR to report on findings from the Texan deployment and to thank station hosts.

Publicity and Outreach

Professional and Technical

Two special sessions were organized for the Fall 2008 American Geophysical Union meeting to further research into the Nevada earthquakes. One was a poster session focused exclusively on the Wells earthquake. The other gathered research on the theme of non-volcanic swarms, and included both oral and poster sessions.

Schools and Education

UNR maintains an active "in-person" community outreach through tours and presentations to visiting students, teachers, and community members. During the reporting period UNR hosted approximately 6000 students and 1000 teachers who came from six counties in Nevada and two in eastern California.

K-12 Teacher Programs and Nevada K-12 Seismic Network

During the summer of 2007 we conducted the 3rd year of the 3-year TEAC (The Earth As a Classroom) project, a competitive grant funded through the State of Nevada NecoTIP (Nevada Collaborative Teaching Improvement Program). This was a collaborative program with the Department of Education, University of Nevada Reno, and the Nevada Seismological Laboratory where teachers participated in 3 hours of classroom work, a one week field trip through the Walker Lane including 2 days at Long Valley Caldera, and were required to submit a paper on the tectonics and historical Geology of the Western US through what they learned during the field experience. Overall about 40 Nevada science teachers participated in the 3-year TEAC program.

Upgrades to the Nevada K-12 network are underway with the installation of Motion Node 2 g 10-bit accelerometers at, ultimately, 20 schools (http://www.motionnode.com/accel.html). Sensors are running at Pahranagat High School, Alamo High School, Churchill County Middle School, Lovelock High School, Yerington High School (PSN instrument), Bishop Manogue High School (Guralp CMG-ESP), and Lone Pine High School. These data are installed on classroom PC's and secured to internal walls with continuous data transmission to UNR. During installation presentation are given to science classes. Participating teachers are those who have been part of the TEAC program and are therefore familiar with Nevada tectonics and earthquake hazard. All TEAC participants in Nevada receive earthquake notification email and a regular dialog is conducted with teachers following significant events. Motion Node accelerometers are being used because the project is not funded and previously operated PSN systems are not practical to maintain. Whereas the PSN stations would record small local events and contribute to regional monitoring, the Motion Node accelerometers will only record large local events on-scale. We are aware of the QuakeWatcher program; however, the Nevada K-12 network provides real-time data feeds to classroom of Nevada area network stations and data from the IRIS DMC. Stations are installed only as time permits, since this is not a funded effort.

Other outreach activity

UNR organized and co-hosted an outreach to community stakeholders, with Chris Poland, Seismological Society of America 2008 Joyner Lecturer, addressing the topic of earthquake resilient communities. Resilience motivates discussion of the post-earthquake recovery phase - the viability of “city hall” to provide plans, inspectors, and approvals; how long critical systems and businesses can be off-line; and what the requirements are for an effective reconstruction workforce.

Selected public presentations

Perhaps the most visible public outreach element in the reporting period was the filming of the National Geographic Channel Naked Science program "Earthquake Swarm", covering the Mogul earthquake swarm (http://channel.nationalgeographic.com/series/naked-science/4232/Overview). Several UNR seismologists, geologists, and staff were interviewed in office, lab, and field settings. The program has been aired several times nation-wide.

"Recent Nevada Earthquakes: Seismic Monitoring for the Wells and Mogul Areas" (Ken Smith, Nathan Edwards), Osher Lifelong Learning Institute, University of Nevada Reno, August 28, 2008

"Recent Nevada Earthquakes: Seismic Monitoring for the Wells and Mogul Areas" (Ken Smith, Nathan Edwards), American Meteorological Society, Reno Chapter, April 22, 2008

Earthquake Safety - pre-school teachers (dePolo, Rennie; attendees: 40)
Earthquake Safety - CEVA Logistics employees (50)
Intensity/Location exercise - College of Engineering Summer Camp (20)
Mogul/Somersett Activity - Sierra Canyons Home Owners (250)
EQ Safety/Mogul-Somersett Activity - U.S. Forest Service (25)
EQ Safety/Mogul-Somersett Activity - Circus Circus Emergency Committee (25)
Wells Mogul-Somersett Activity - Galena High School (65)
Wells Mogul- Somersett Activity - US Bankruptcy Federal Building (65)
Wells Mogul- Somersett Activity - Governor's Safety Conference (25)

Wells Mogul- Somersett Activity - Elderhostel Group Classical Residence (50)
Reno Gem and Mineral Society (55)
Retired Public Employees (50)
American Society of Safety Engineers (ASSE) Sierra Board (13)
Local PM group (30)
Teaching Teachers sponsored by Nevada Mining Association (60)

Booths (de Polo, Rennie)
Boy Scout Safety Fair
City of Reno Safety Fair
Governor's Safety Conference

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Also, see Appendix A for chapter contributions to the Wells volume.

Abstracts

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"What Can We Learn From the Wells, NV Earthquake Sequence About Seismic Hazard in the Intermountain West? ", (Contributed Poster), M. Peterson, K. Pankow, G. P. Biasi, M. Meremonte, American Geophysical Union Fall Annual Meeting, American Geophysical Union, San Francisco, California. (December 19, 2008).

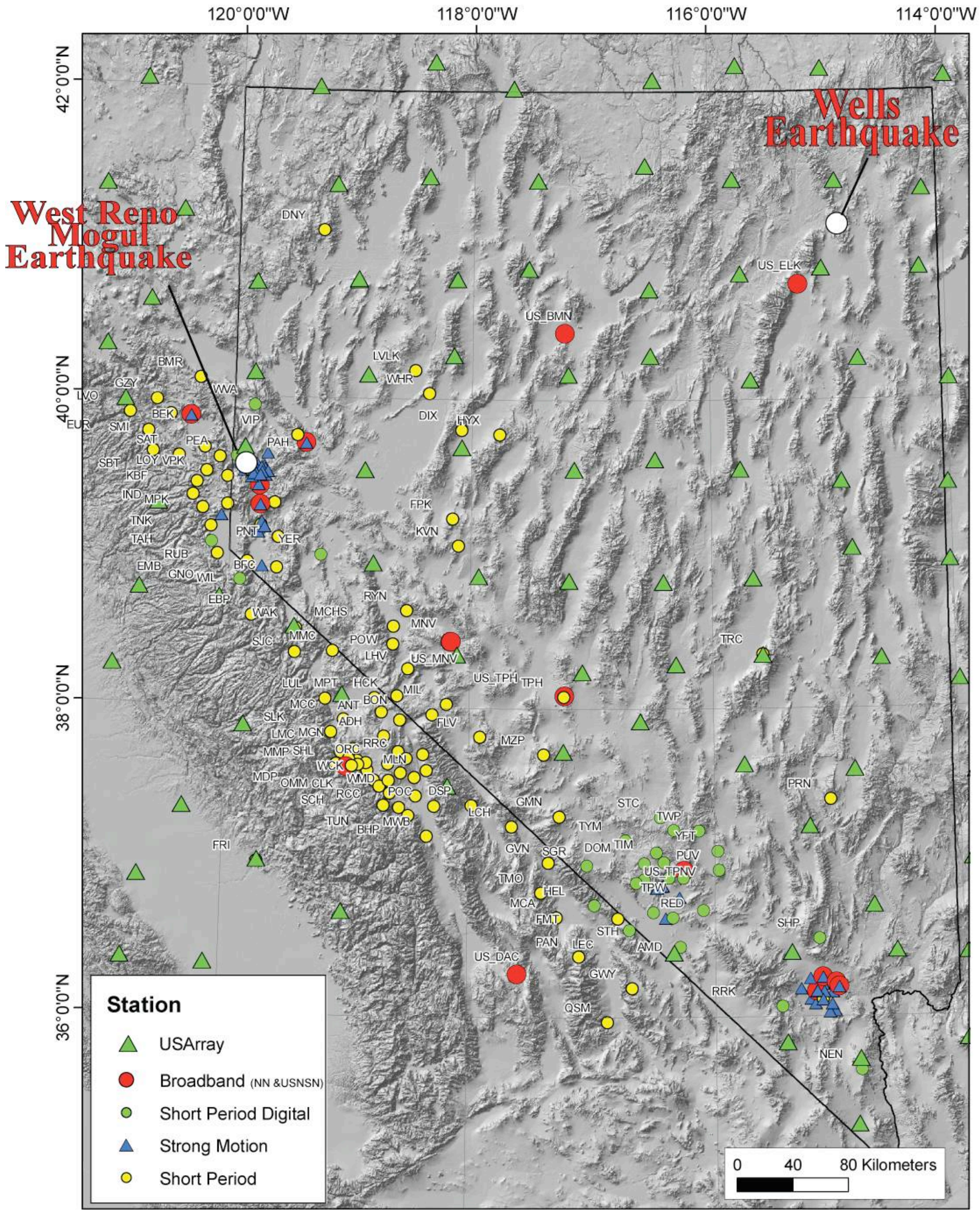

Figure 1. Seismic stations contributing to UNR network monitoring. USArray stations (triangles) began in Nevada in 2006 and departed in late 2008. The cluster of stations centered south of US_TPNV are digital 3- and 6-component stations of the Yucca Mountain seismic monitoring network. Outside of this area, spatial coverage of the network is primarily provided by short-period analog stations. ARRA funding will upgrade several short period digital stations to broadband, but analog stations are programmed to remain for the foreseeable future.

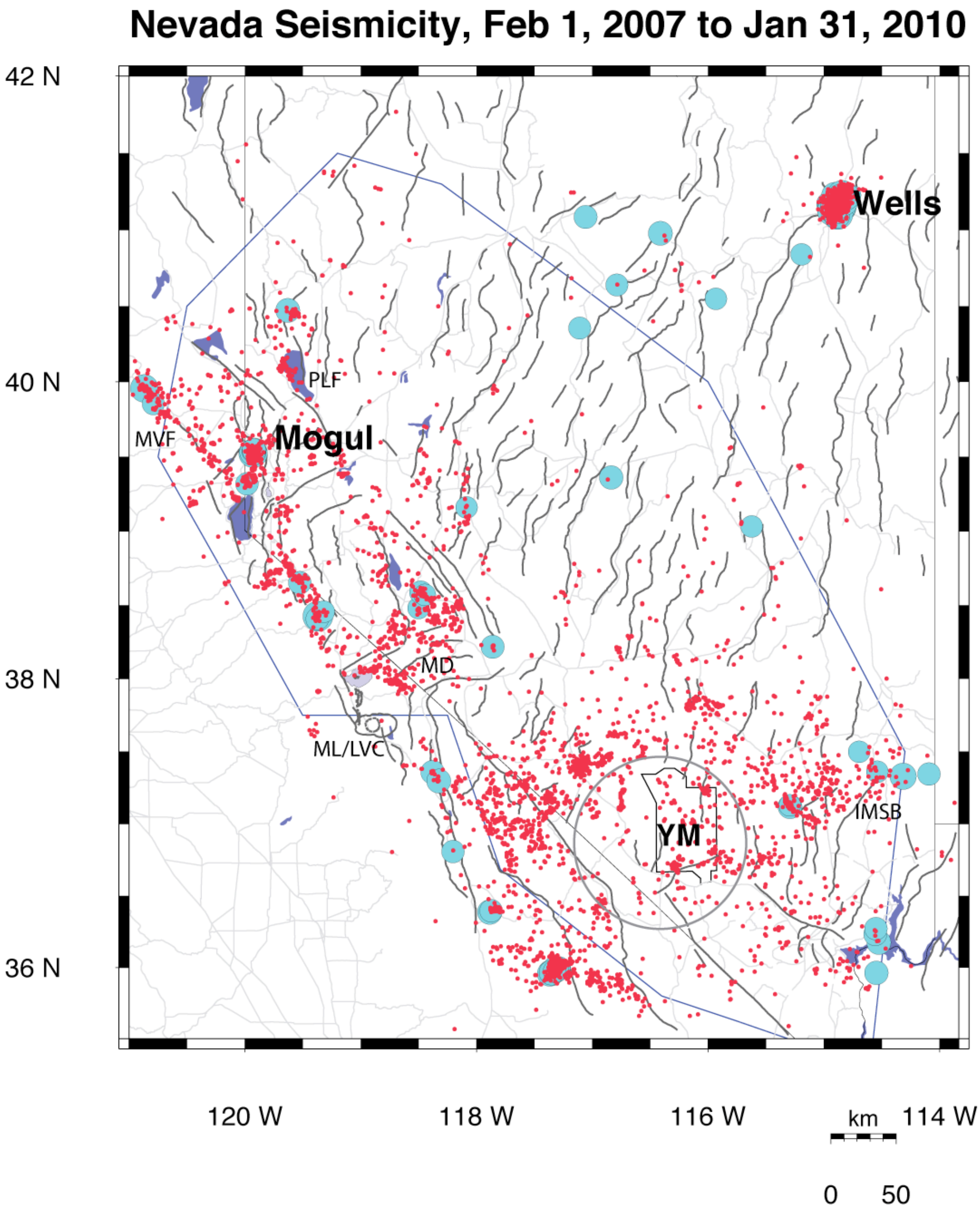

Figure 2. Earthquakes located during the reporting period. Red dot are 1.0≤M<3.5 earthquakes with at least 8 associated phases. Blue circles are M≥3.5 events, with larger symbols for larger earthquakes. MVF: Mohawk Valley Fault; PLF: Pyramid Lake Fault; MD: Mina Deflection; ML/LVC: Mammoth Lakes/Long Valley Caldera; IMSB: Intermountain Seismic Belt; YM: Yucca Mountain, at left side of the YM. The gray circle around YM is the 65 km radius special catalog area for Yucca Mountain, where especially thorough earthquake recovery was exercised for DOE. The YM network has helped with locations of earthquakes all around the special focus area.

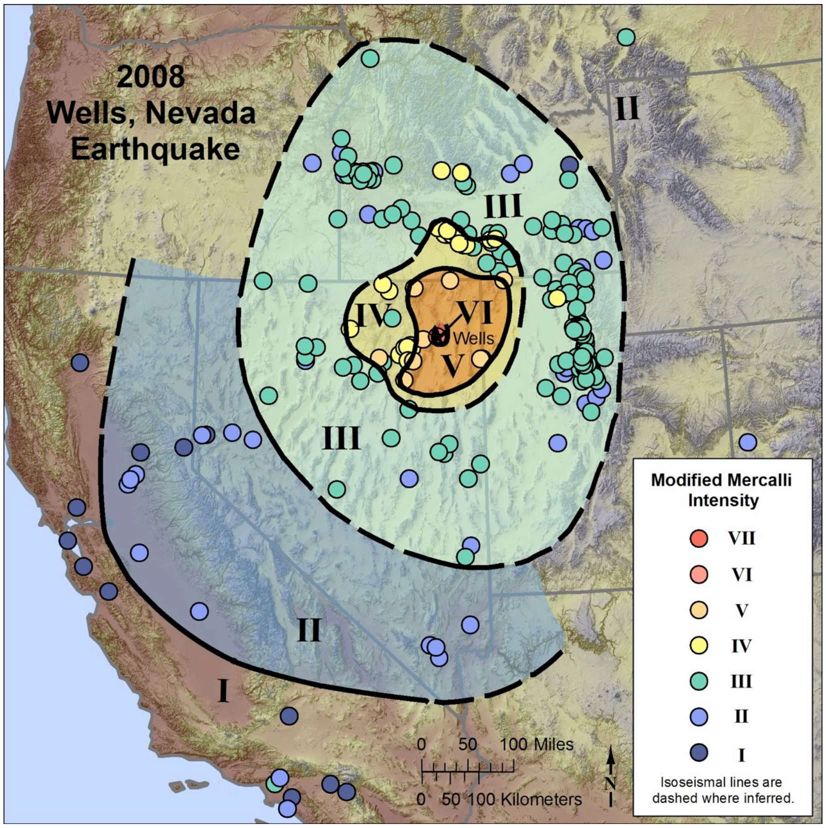

Figure 3. Regional intensities reported for the 2008 Wells, Nevada mainshock.

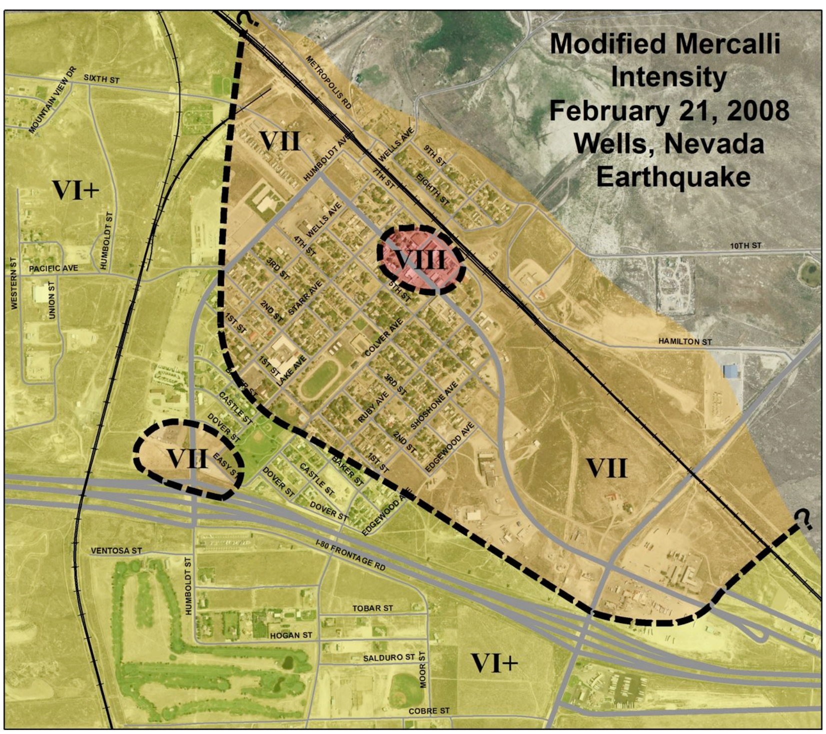

Figure 4. Local MMI estimates for the Wells mainshock. Most of the damaged or destroyed old-town buildings were in the small zone at MMI VIII.

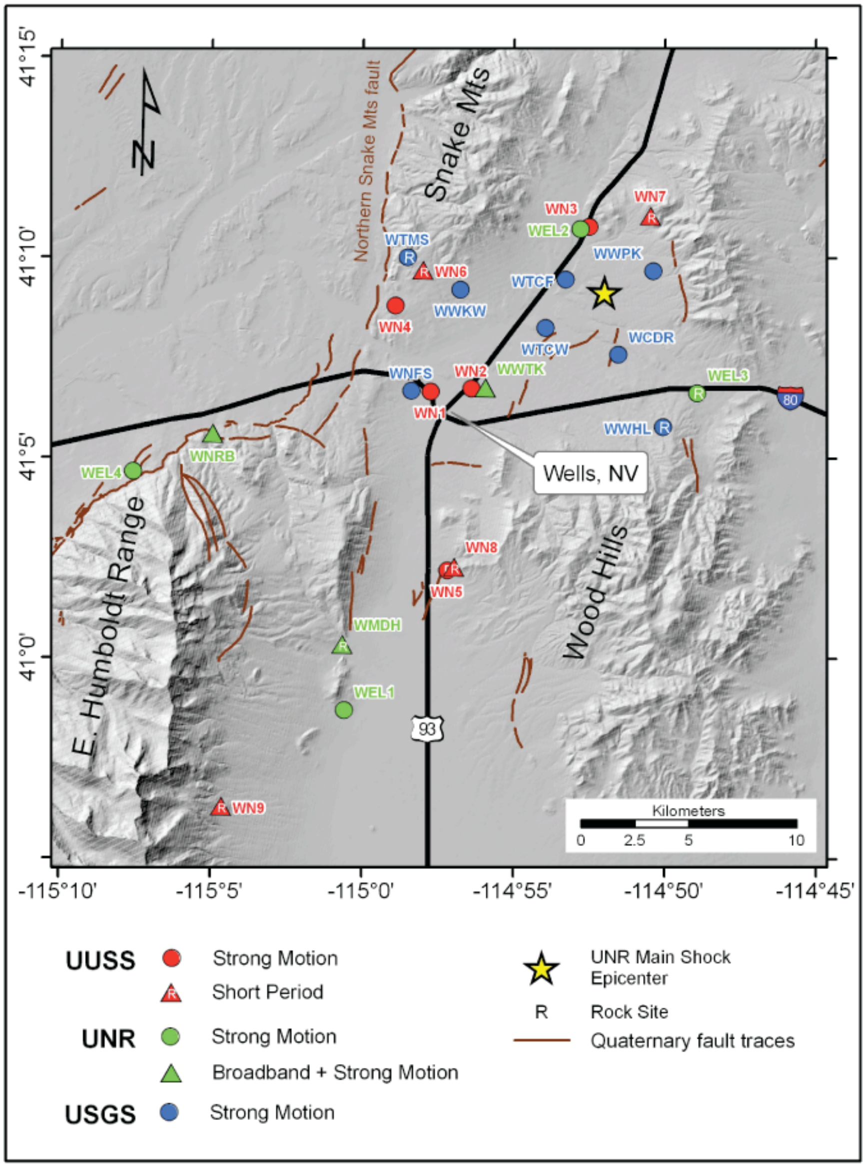

Figure 5. Wells, Nevada seismic station coverage. All stations on this map were installed after the mainshock.

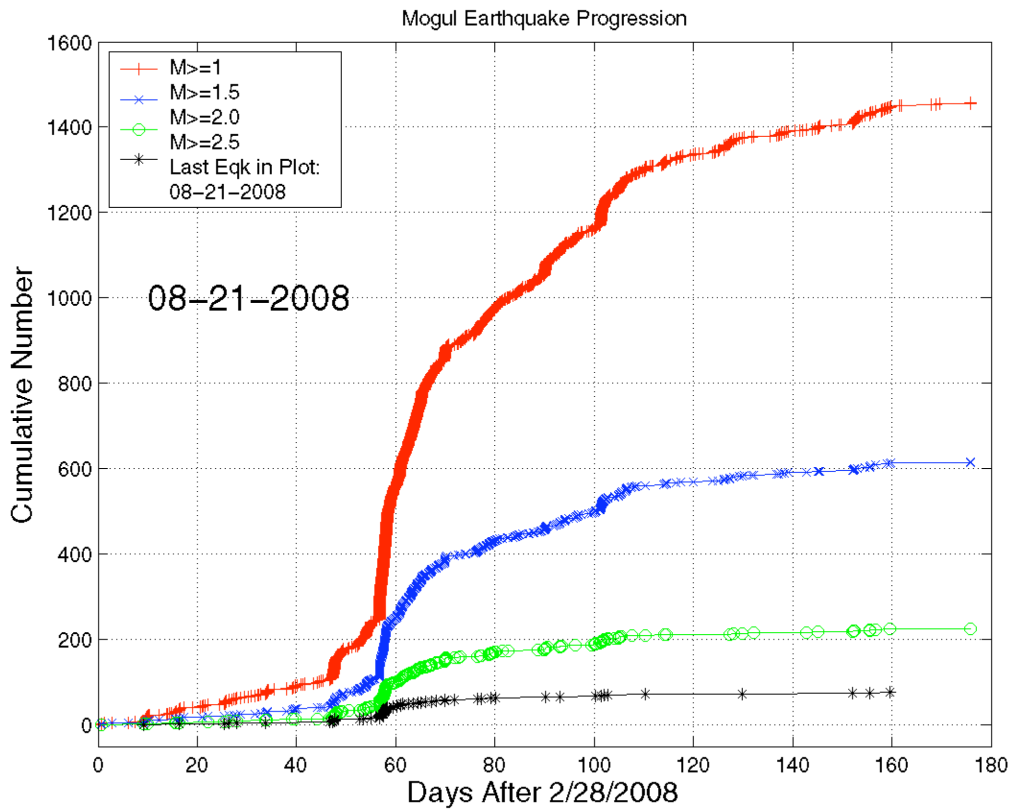

Figure 6. Cumulative earthquake occurrence versus time. The mainshock occurred about a day after the steep up-tick on day 57.

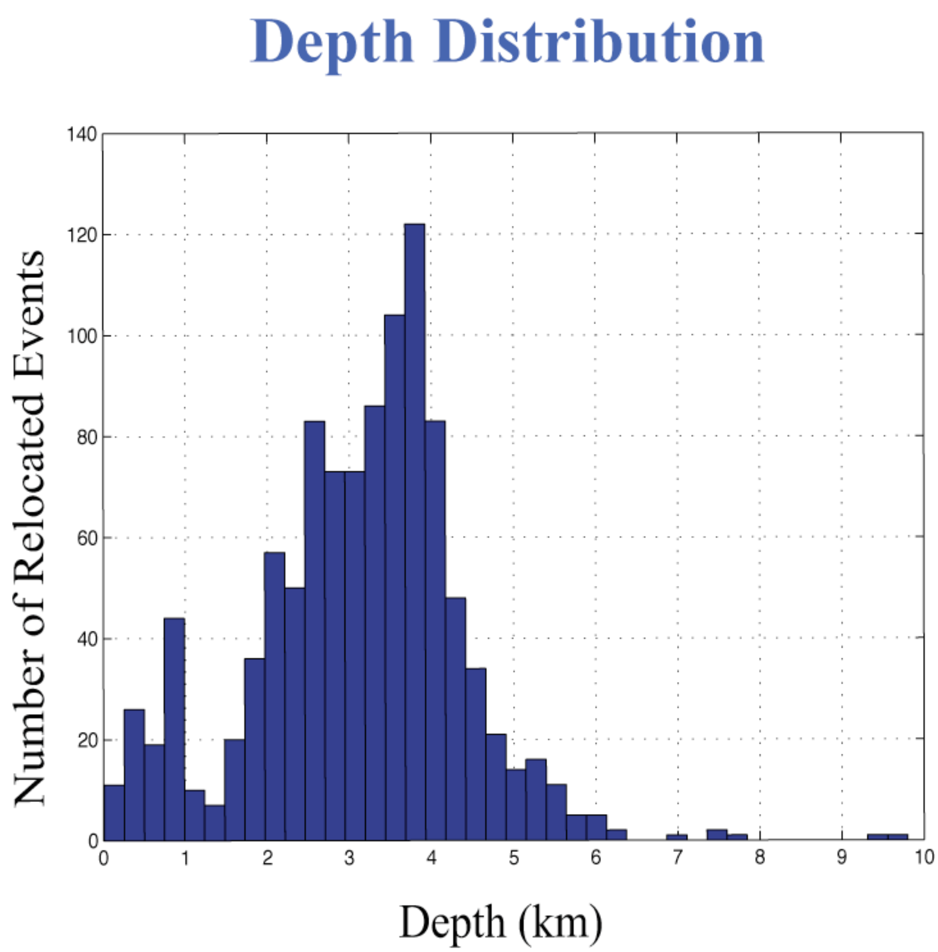

Figure 7. Depth distribution of the Mogul, Nevada swarm. The mainshock hypocentral depth was estimated at 3.1 km. Two seismic stations were located less than a few hundred meters of the epicenter.

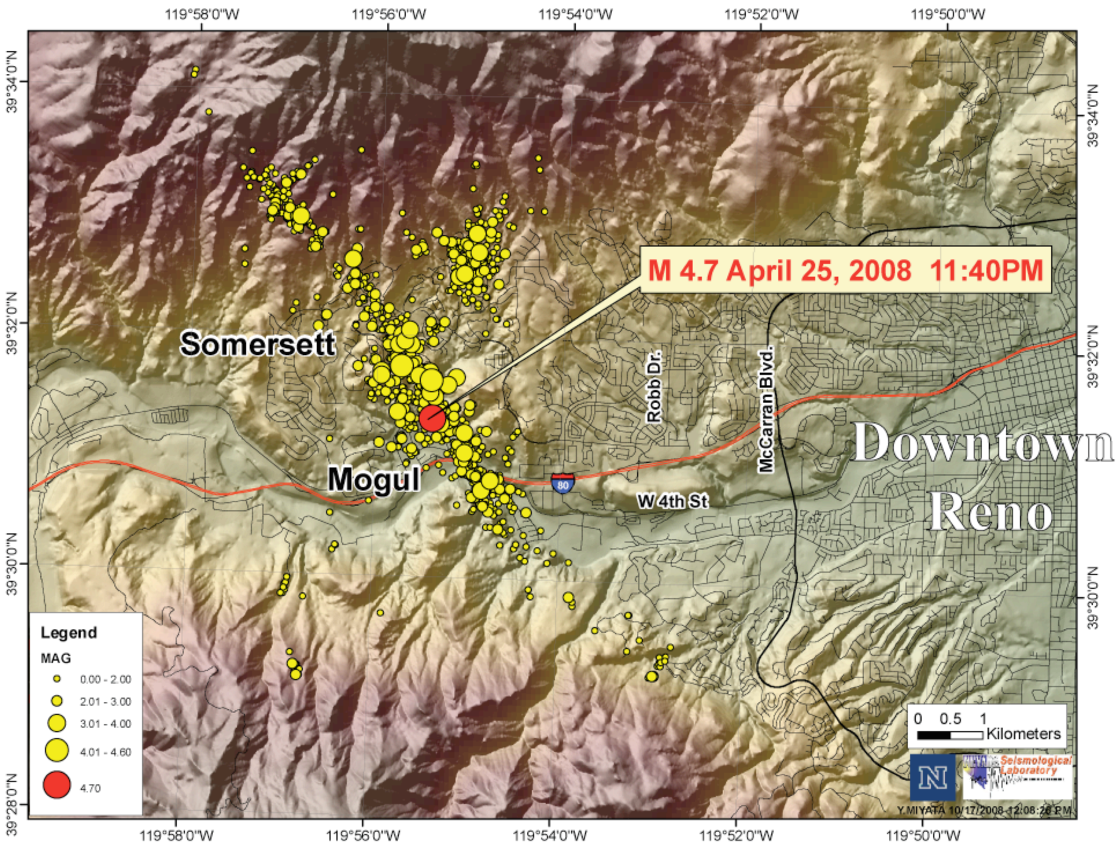

Figure 8. Relocated seismicity of the Mogul earthquake swarm. M 4.7 refers to the M_L estimate. This event is unusual not only for its presentation as a swarm, but also because geodetically identified afterslip exceeds the moment magnitude of the mainshock. The sequence did not occur on a known or suspected active fault structure.

Mainshock Peak Accelerations in Reno

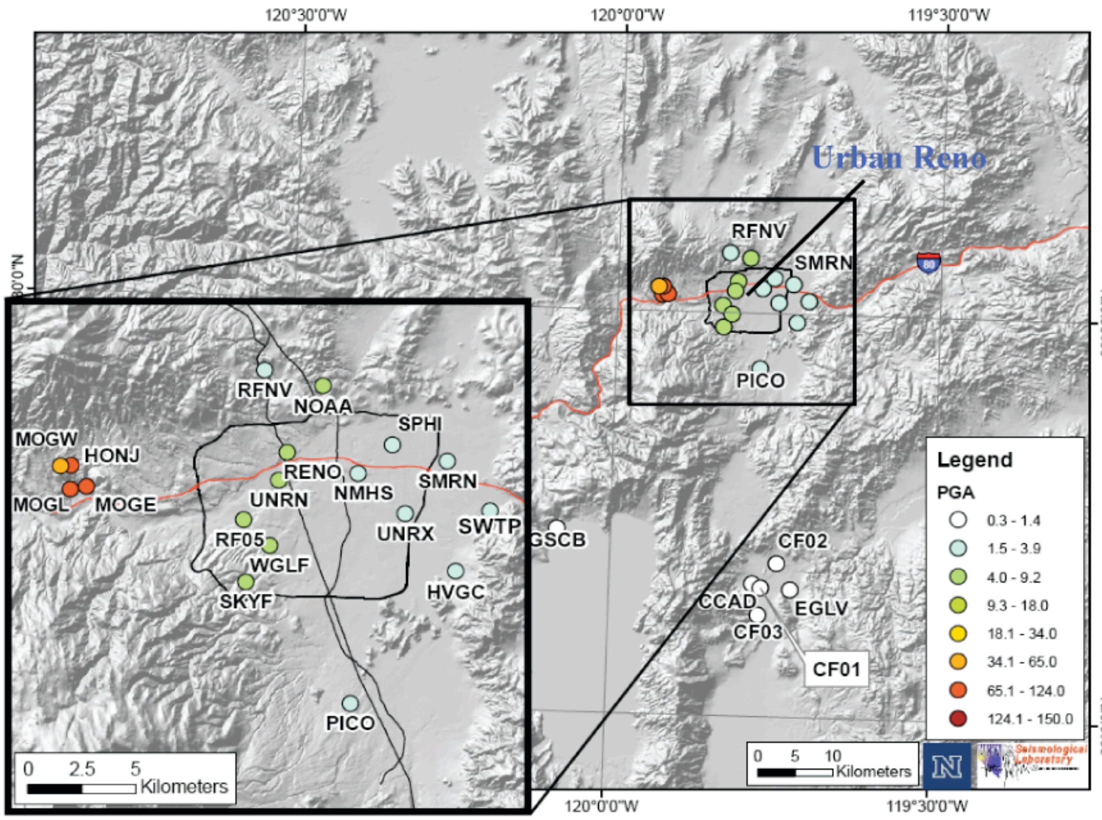

Figure 9. Reno area mainshock peak ground accelerations. Inset shows the four Mogul area portable stations installed and recording at the time of the event. Ground motions away from the epicentral distance were below predicted, perhaps because of the shallow hypocentral depth and thus greater attenuation near the source than a deeper earthquake might have.

Appendix A: **The 2008 Wells, Nevada Magnitude 6 Earthquake Volume**

(Provided by Dr. Craig de Polo, Nevada Bureau of Mines and Geology, Wells earthquake geologic investigator and technical editor of the Wells Earthquake Volume)

On February 21 at 6:16 a.m. PST northeastern Nevada was struck by the largest earthquake to occur in the Basin and Range Province in the last 15 years and the largest event in Nevada in the last 42 years. The Nevada Seismological Laboratory (NSL), the Nevada Bureau of Mines and Geology (NBMG), and the Nevada Earthquake Safety Council (NESC) were determined to study, understand, and document this event, and to cast the data and experiences into lessons learned that could be distributed and engaged in for a seismically safer Nevada and beyond. Thus, the usual scientific response was conducted with a temporary seismic array, field studies for surface fractures, and hundreds of pictures were taken of the damage and effects, and many universities and organizations were involved, notably the University of Utah Seismograph Stations (UUSS), the Utah Geological Survey (UGS), and the U.S. Geological Survey (USGS) in addition to the Nevada responders and scientists. But interest in this event waned a few months later and it was slightly overshadowed by an earthquake swarm near Reno, Nevada that occurred a few months later. This is when the importance of the Nevada, the USGS, and the Federal Emergency Management Agency (FEMA) commitment to documenting this major earthquake and its effects became even clearer.

With support from the USGS, the FEMA, and the NESC we developed a Wells earthquake volume that would be placed on the web and would encourage all researchers involved in studying the event to submit their research to the volume in the form of peer-reviewed papers. The Wells earthquake volume web site will be opened in late spring or early summer 2010. Twenty-eight papers were submitted, collected, and developed, along with a local geologic map, an InSAR image of the earthquake, and hundreds of photographs of the earthquake effects. In a few cases, we proactively invited scientists to submit papers to more completely cover important aspects of the earthquake. To maximize the benefits of the Wells earthquake volume papers on topics including the geologic and Quaternary fault setting; the seismic hazard setting; seismological, geophysical, and geodetic aspects of the earthquake; damage to buildings and houses; the emergency response, community recovery, and impact on city government; and numerous photographs, images, and a video made by the local community.

Scientifically, we were fortunate to have had a temporary seismic array, the Earthscope USArray Transportable Array, in Nevada before, during, and after this event. This network provided vital broadband recording that captured foreshocks, the mainshock, and aftershocks with high-quality instruments. The immediate response by NSL, UUSS, and USGS seismologists installing a local seismic array in resulted in the detailed recording of aftershocks and ground motions in damaged areas, which has given our most detailed understanding into the physics of the Wells Earthquake and gave some fundamental insights into the damage that occurred.

Our understanding of the impact of a major earthquake on a rural community was also profoundly increased. Prior to the Wells earthquake the Nevada Earthquake Safety Council, the Utah Seismic Safety Commission, and the Basin and Range Province Committee of the Western States Seismic Policy Council all expressed concern that there was a lack of understanding and experience in rural earthquake disasters. Resources and planning had been naturally focused on the urban areas that have higher risk than rural communities. But with so many rural and frontier communities scattered throughout the western United States, the likelihood of a rural earthquake disaster is greater. The question they raised is, "Do we respond the same to a rural community disaster as an urban disaster, or are there details, strategies, and logistics that could be more effective?" The Wells earthquake gave us great insight into this question. These themes are explored in the volume.

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Selected Results Presented in the Wells Earthquake Volume

The 2008 Wells Earthquake occurred in northeastern Nevada, an expansive region with relatively few recorded or historical earthquakes. Seismic instrumentation has generally been sparse. Anderson (Wells volume) estimates from background seismicity that earthquakes of Mw=6.0 or larger can be expected with an occurrence rate of ~0.01 per year over a region of ~10,000 km^2 in northeastern Nevada. Thus, the occurrence of this once-a-century earthquake is consistent with that estimate. Although the occurrence of this event next to a community in this sparsely settled region seems small, Anderson points out that the results are consistent with a USGS National Hazard Map estimate for Wells.

The geologic setting has been laid out in two papers, one by Thorman and Brooks and the other by Henry and Colgan (Wells volume), and a 1:48,000 scale geologic map of the area produced by Henry and Thorman for the volume. These scientists describe a detailed geologic and tectonic history of the region with some structures, such as the "Wells fault", possibly being inherited from the Precambrian basement and being reactivated several times since. Local basin structures and mountains have been formed over about the last 20 million years when widespread extension occurred. This extension also tilted local geologic structures and created the basin that underlies Town Creek Flat and Marys basin to the west. Henry and Colgan suggest that the Wells earthquake may have occurred on a previously unmapped northern projection of the Clover Hill fault; this fault is exposed south of Wells and has geomorphic expression of Quaternary activity. Ponce and others (Wells volume) used gravity and magnetic data to investigate the geophysical setting of the Wells region. In particular, they developed the geometry of the local basin adjacent to Wells that likely was important in influencing ground motions (amplitude and the duration) that were experienced at Wells and damaged buildings. Ponce and others made a new depth-to-basement map, mostly based on gravity, that indicates that the basin below Town Creek Flat is rhomboid shaped and reaches a depth of 2 km north of Wells. Ramelli and dePolo (Wells volume) examined local Quaternary faults and summarized the search for surface cracking from the earthquake. The fault on which the earthquake occurred was not previously recognized. There are, however, geomorphic lineaments and short possible scarps within the Snake Mountains near the surface projection of the well-located aftershocks reported by Smith et al. (Wells volume), but whether there is a Quaternary fault at the surface is equivocal. No surface cracking was found, but conditions were not favorable for exploration at the time of the event and exploration could only be completed months later. Cracking similar to what occurs seasonally also cannot be ruled out. Overall, it is likely the Wells earthquake was a buried or "blind" event, and could reasonably be considered a background earthquake.

The February 21, Wells earthquake was a normal faulting event with a seismic moment of 1.3×10^{18} N-m, corresponding to a moment magnitude of $M_w = 6.0$ (USGS CMT; Smith and others, Wells 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 and provided good location control for foreshocks, the mainshock, and early aftershocks, and twenty-seven portable seismometers were deployed to the region for detailed aftershock and ground motion studies (Smith and others, Wells volume). Smith and others note that the mainshock had nearly pure normal displacement on a fault with a strike of N30°E, and a dip of 55°SE based on relocated aftershocks. Smith and others note that there is a roughly 8-km-diameter circular area in the aftershock plane that is nearly free of events. They interpret this as area of the mainshock, 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. The seismograms from regional stations, including USArray, were used by Dreger and others (Wells volume) and Mendoza and Hartsell (Wells volume) to develop finite source models for the event. Dreger and others calculated a moment-tensor solution and a finite-source solution using analyses of waveform data and interferometric synthetic aperture radar data. The results are a fault with a northeast strike and southeast dip, similar to that found by Smith and others (Wells volume). Their finite-fault solution shows small patches of displacement in the fault plane; the greatest amount of slip, 103 cm, is in an area that lacks aftershocks; modeling indicates most of the slip during the earthquake was below 4 km. Mendoza and Hartzell used a kinematic, finite-fault inversion procedure to develop their model; they find the coseismic slip occurring in an area of 4 x 6 km, with the greatest slip, 88 cm, occurring near the hypocenter. Their model is a bilateral rupture where coseismic slip occurs in about two seconds.

Petersen and others (Wells volume) review the seismic hazard for Wells that is indicated on the National Seismic Hazard Maps (NSHMs) and documented the ground motions recorded for the 2008 Wells earthquake and an Mw=4.7 aftershock. The NSHMs indicate a peak ground acceleration of 0.2 to 0.3 g for the Wells region, with a 1 in 2,475 chance of being exceeded annually. When this hazard is deaggregated, 50% of the contribution is from background earthquakes, like the Wells earthquake. The ground motions for the Mw=6.0 Wells earthquake were only recorded at distances of 37 km and greater; Petersen and others found peak ground motions to be generally compatible with ground-motion-prediction equations used in the National Seismic Hazard Maps, which is an important positive result. Closer ground motion recordings were made of aftershocks by the portable seismic array. One of these aftershocks, an Mw=4.7, was recorded at the Wells Fire Station, which is within 100 m of the highest damage levels found from the mainshock (Modified Mercalli Intensity VIII); the fire station is on a soil site and was a little less than 10 km away from the aftershock's epicenter. Petersen and others report that shaking from this aftershock at this site "exceeded 0.2 g and experienced sustained accelerations above 0.1 g for about 5 seconds." Thus, an aftershock produced ground motions consistent with those indicated in the NSHMs for the Wells region. Because there was severe damage near the fire station during the mainshock and it was over a magnitude unit higher and in the same location, or closer, than the recorded aftershock, it is likely the mainshock had even more severe ground motion.

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

Hammond and others (Wells volume) examined 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 and 1.0 ±0.2 mm, respectively (Hammond and others, Wells volume). Hammond and others found the magnitude and direction of these, and other GPS displacements, were in agreement with those predicted from rupture models of the earthquake. 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 (Wells volume) calculated changes in static Coulomb stress that were imparted by the Wells earthquake on nearby faults. Sevilgen found the largest 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), and small decreases in stresses on other local faults.

Earthquake damage was portrayed in Modified Mercalli intensity maps, economically, and in building-by-building detail. Damage in the historical district of Wells was characterized by collapsed and partially collapsed buildings and reached a level of Modified Mercalli Intensity (MMI) VIII (dePolo and Pecoraro, Wells volume). In the northern half of Wells, damage included broken and fallen chimneys and widespread nonstructural damage corresponding to MMI VII (dePolo and Pecoraro, Wells volume). Three houses were destroyed by the earthquake (out of ~450 houses) and over 60 chimneys were damaged (dePolo, Wells volume). Out of about 80 non-residential buildings, about half of these were damaged and in 10 of these buildings, the damage was severe. Four buildings totally or partially 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, Wells volume). The Wells High School gymnasium and auditorium were both structurally damaged (Trabert, Wells volume), and required a concerted effort to get the buildings restored within six months time to be ready for the following school year. Repairs were completed in time, at a cost of $2.478 million.

The 2008 Wells earthquake cost the community of Wells over $10 million. This can be further broken down into response costs $300,000, direct damage costs of at least $7.678 million, nonstructural damage costs of at least $867,000, and indirect costs of $1.746 million. The amount of relief, earthquake insurance coverage, and disaster funding and loans totaled $6.689 million, $4.836 million of which was paid out by earthquake insurance. The cost of the earthquake, minus the relief, insurance, and disaster funding, leaves about $3.6 million of permanent loss to the community.

The emergency response effort to the earthquake disaster was very effective. Approximately 100 personnel and 40 pieces of equipment responded, and most arrived on scene in less than an hour after the event to assist. The recovery of the town was mostly completed within two years, including the reconstruction of most buildings that were in use at the time of the event. Wells is looking forward to the construction of new city facilities that will be replacing the city's unreinforced masonry buildings, which were damaged from the earthquake.

Lessons learned from the 2008 Wells earthquake are documented throughout the papers, but a focused paper by the Nevada Earthquake Safety Council summarizes the major lessons, including lessons for Nevadans on being prepared for earthquakes, 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, lessons about emergency response and recovery, and an appeal for increased earthquake monitoring capability and Quaternary fault studies in the state.

In all, the Wells earthquake volume has successfully captured many aspects of the earthquake and its aftermath, and documents a rural earthquake disaster for further analysis. Papers have been submitted, reviewed, and revised. A few papers have been typeset, most are in the revision stage, and a couple of papers that are still in review. The web site for the earthquake volume will likely be opened by July of 2010, when all papers are complete.