Final Report: Nevada Seismic Network
USGS Cooperative Agreement for Seismic Network Operations

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C.A. Start Date & End Date: 2/1/2010 – 1/31/2015
Seismic Network Web Site: http://www.seismo.unr.edu
Network Code: NN
Network Name: Western Great Basin Seismic Network
ANSS Region: IMW
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Introduction

Historically, Nevada has been the 3rd most seismically active state in the nation, behind only Alaska and California. Nevada owes this distinction in large part to the Walker Lane deformation belt that straddles the California–Nevada border, accommodating roughly 75% of Intermountain West deformation (or ~20% of the total plate boundary strain; Unruh et al., 2003; Wesnousky, 2005). During the '2010/2/1-2015/1/31' USGS Advanced National Seismic System (ANSS) Cooperative Agreement period, the Nevada Seismological Laboratory (NSL) located **59,793** earthquakes within the Nevada and eastern California region. Event locations and magnitudes are archived at the Northern California Earthquake Data Center (NCEDC), the USGS ComCat archive in Colorado, and locally at NSL. There are some differences in catalog compilations; the NCEDC catalog is based on ANSS authoritative regions established in the early 2000s, whereas ComCat accepts all contributions. Of all earthquakes located by NSL during the 5-year period, about 5,000 fall outside the bounds of the older NSL ANSS authoritative boundary, mainly in eastern California, and many of these are also located by California networks.

NSL responds to all Magnitude ≥ 3 earthquakes, 24/7, and submits data analysis products to the USGS ComCat catalog via QuakeML messages that are transferred through the PDL interface. These products include reviewed event locations, phase data, event uncertainties, ShakeMaps, and moment tensor solutions for Magnitude ≥ 3.5. The information is also posted on the NSL web page. NSL is actively engaged with the Nevada Earthquake Seismic Safety Council, regularly responds to media requests and interviews, and issues press releases following notable events and during active earthquake swarms.

Table 1. Earthquakes, by Magnitude, Located by the Nevada Network, 2010/2/1 – 2015/1/31.

Total Number of Events Located:	**59,793** *
Magnitude ≥ 5.0:	3
Magnitude ≥ 4.0:	53
Magnitude ≥ 3.0:	505
Magnitude ≥ 2.0:	3283

*(includes some events outside of NN ANSS authoritative area)

Within the NCEDC-hosted National ANSS earthquake catalog, NSL accounts for over 60% of all Intermountain West earthquakes (Nevada+Utah+Mountain+Wyoming). The largest event within the NSL network region during this recent 5-year period was the 2013 magnitude 5.1 Mina, Nevada earthquake (Coaldale earthquake); NSL also played a role in response to the 2013 northern California M5.6 Lake Almanor/Canyon Dam sequence, installing temporary instruments to supplement northern CA operations. Prior to the August 2014 Mw6.0 Napa, CA event, the most recent Mw6 earthquake in the continental U.S. (sub-aerial) was the 2008 Wells, Nevada Mw6.0. Although earthquake activity has been brisk over the past 5 years, it pales in comparison to the early part of the 20th century, where Nevada experienced no fewer than seven M6.5+ earthquakes between 1915 and 1954; it has now been 60 years since the Silver State has experienced its last M6.5+ earthquake, and earthquake response, preparedness and regional monitoring will be key to public response to the next large event. Since 1954, Nevada's population has increased dramatically to ~2.75 million residents, or an increase of ~1300%. The largest urban district in Nevada, the greater Las Vegas Valley, now has a population of 2 million residents, with as many as an additional 300,000+ visitors on special event weekends. The most recent release of the USGS Hazard map (Petersen et al., 2014) saw most regions in Nevada unchanged in terms of seismic hazard (Fig. 1), though the greater Las Vegas region received a meaningful uptick in hazard owing to recent paleoseismic and modeling studies (Lamichhane et al., 2014). Evidence of Holocene ruptures and new geodetic studies (Kreemer et al., 2013) help define an important shear zone in southern Nevada that transfers slip to the Wasatch Range in Utah, from the Eastern California Shear Zone/Walker Lane of western Nevada. This is a significant tectonic structure affecting Nevada citizens; yet monitoring in the populated areas in southern Nevada is poor at best. Fortunately, over the next five years, with support from the USGS, additional monitoring stations will be installed in the Las Vegas area.

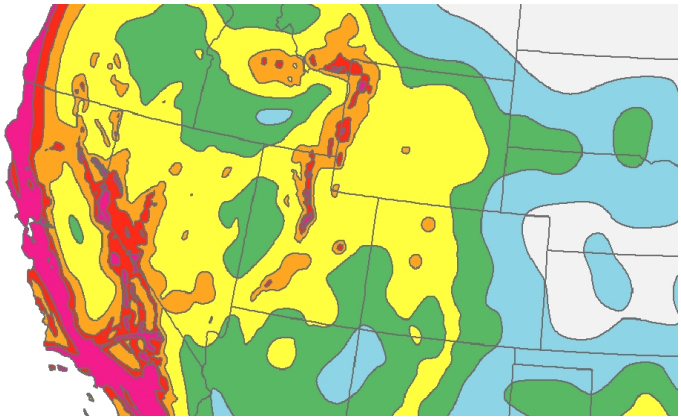

Figure 1. USGS 2014 Seismic Hazard Map highlighting relative hazard in the western U.S. Seismic monitoring contributes to the development of USGS Seismic Hazard Maps.

Earthquake Monitoring Purpose, Objectives and Results

The Nevada Seismological Laboratory's (NSL) regional seismic network operations have continued to modernize in accordance with the goals and vision of an Advanced National Seismic System (ANSS). Network operations at NSL must support earthquake response for the 3rd most seismically active state in the U.S., requiring earthquake processing at a rate ~12,000 events per year over the past five years.

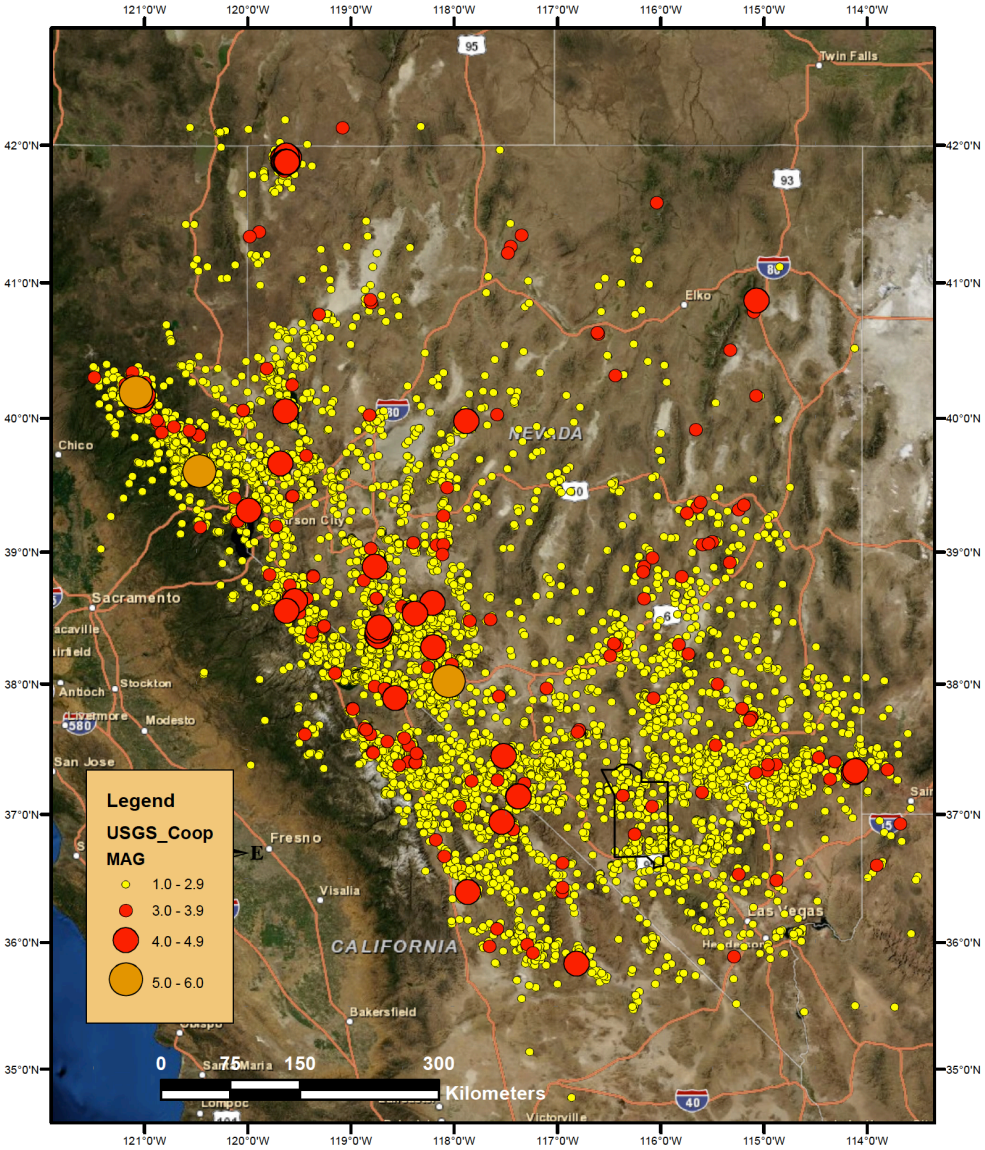

Figure 2. Earthquakes reported to the ANSS 2010/2/1 through 2015/1/31 for Nevada, E. California and SW Utah; shown are locations of ~18,000 earthquakes Magnitude ≥ 1.0.

Figure 3 shows yearly recurrence rate curves from the NCEDC-hosted earthquake catalog for other western US seismic networks. The weekly rate of M3+ earthquakes (Table 2) mirrors the tectonic plate rate division, with Nevada bearing 20% of the western US total.

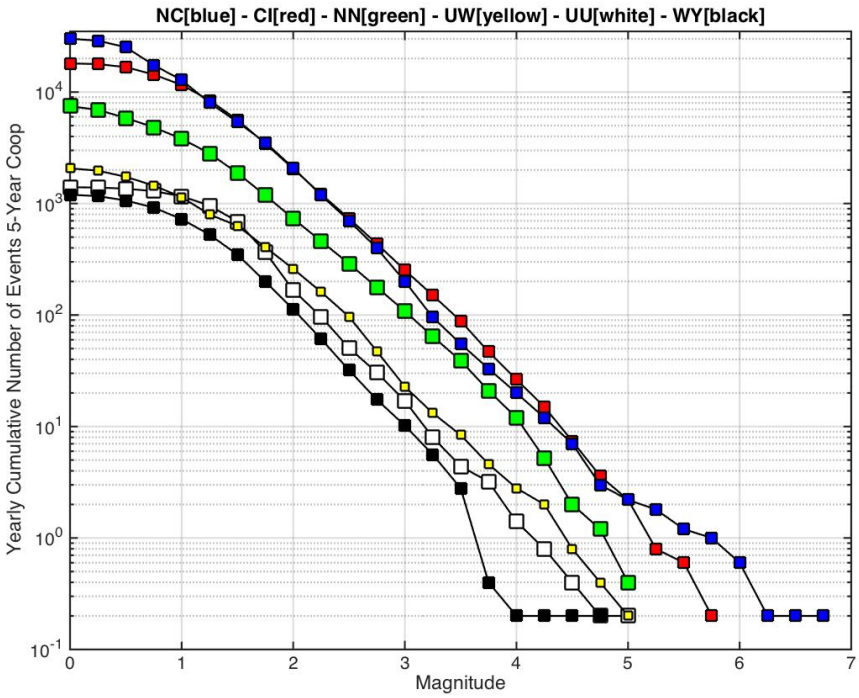

Figure 3. Yearly recurrence rates for the past 5 years for western US seismic network from the NCEDC ANSS earthquake catalog; **CI**-Southern California**,** **NC**-Northern California**,** **NN**-Nevada**,** **UU**-Utah**,** **UW**-University of Washington**,** and **WY**-Wyoming/Yellowstone.

Table 2. Summary of Events by Magnitude for Networks Shown in Figure 3

Magnitude ≥	6	5	4	3	M ≥ 3/wk*
CI		5	97	991	3.8
NC	2	10	75	615	2.4
NN		2	42	445	1.7
UU			4	62	0.2
UW			12	88	0.3
WY			1	39	0.2

* Translates to the number of M ≥ 3 events per week per network

- Network code references in Figure 3 caption.
- Summary is based on the NCEDC ANSS Catalog compilation.

A recent compilation of historical Magnitude 6+ earthquakes (Table 3, Fig. 3) by Craig dePolo (Nevada Bureau of Mines and Geology) illustrates Nevada and eastern California's earthquake potential, which is also reflected in the recent seismic hazard map (Fig. 1) and Table 1. This compilation emphasizes the activity rate through time along the Nevada-California border and underscores, along with the current rate of seismicity, the need to effectively monitor the Walker Lane deformation belt of California and western Nevada (Unruh et al., 2003; Wesnousky, 2005). Although historically cast in the Basin and Range Province, the Walker Lane accommodates ~20% of the plate boundary strain budget

between Pacific and North American plates. Furthermore, of the approximate 13 mm/yr of strain observed between stable North America and the Sierra Nevada/Great Valley microplate, some 75-80% is localized in the Walker Lane. The majority of this strain occurs as dextral shear. Significant range bounding faults along the Sierran front have, in the past, characterized the western Basin and Range as a proxy for the eastern Sierran boundary, however this is not technically correct. Strain partitioning along the eastern edge of the Sierra places primary normal faulting along the front-range (e.g., Tahoe/Genoa systems, Ramelli et al., 1999; Kent et al., 2005), whereas the shear, strike slip faulting, and the largest contribution to the hazard, is seen within 10s of kilometers east of the Sierran range front. Deformation is also associated with rotation and translation of larger crustal blocks (Wesnousky et al., 2012; Dong et al., 2014).

Table 3. Historical Magnitude 6+ (and notable M5+) within the NV-CA Border Regions (not eastern and central NV).

YEAR	MAG	LOCATION	STATE	INTERVAL
1790s?	7+?	Owens Valley Region	CA	-
1852?	6+?	Pyramid Lake	NV	-
1855	6.0	Sierraville	CA	-
1857	6.0	N of L. Tahoe	CA-NV	2.7 YR
1860	6.5	SW of Pyramid Lake	NV	3 YR
1868(2)	6.0	S of Reno	NV	8 YR
1869	6.4	S of Reno	NV	1.25 YR
1869	6.2	S of Reno	NV	8 HR
1872	7.9	Owens Valley	NV	2.3 YR
1872	6.8	Owens Valley	NV	3.5 HR
1872	6.3	N. Owens Valley	CA	8 DYS
1872	6.8	Round Valley	CA	8 DYS
1875	6.2	Diamond Mtn.	CA	2.75 YR
1885	6.1	Susanville	CA	10 YR
1887	6.5	Carson City	NV	2.3 YR
1889	6.2	Susanville	CA	2 YR
1889	6.0	S. of Mammoth Lakes	CA	3 MO
1896	6.3	Independence	CA	7 YR
1908	6.0	Panamint Range	CA	10 YR
1910	6.1	S of Columbus Marsh	NV	2 YR
1914	6.0	Reno	NV	3.25 YR
1914	6.4	Reno	NV	65 DYS
1916	6.1	E. of Death Valley	CA	2.5 YR
1927	6.0	NW of Bishop	CA	11 YR
1932	7.1	Cedar Mountains	NV	5 YR
1933	6.0	Wabuska	NV	6 MO
1934	6.1	Excelsior Mountains	NV	5 MO
1948	6.0	Verdi	NV	14 YR
1950	5.6	Fort Sage Mountain	CA	-
1966	6.0	Truckee	CA	16 YR
1980	6.1	Long Valley	CA	14 YR
1980	6.0	Long Valley	CA	16 MN
1980	6.1	Long Valley	CA	2.9 HR
1980	6.2	Long Valley	CA	1.8 DYS
1986	6.4	Chalfant Valley	CA	6 YR
1993	6.2	Eureka Valley	CA	7 YR
2008	5.0	West Reno	NV	
2014	----	----------	-----	22 YR

INTERVAL = Time since prior M6.0+ event

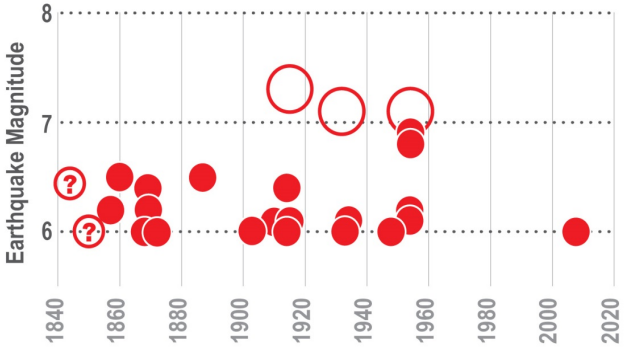

Figure 4. Time line of Magnitude 6 earthquakes in Nevada (does not include E. CA).

Figure 4, in contrast to Table 3, shows a time-line for Magnitude 6 or larger Nevada-only earthquakes, which highlights the hiatus since the late 1950s (a somewhat different set than Table 3). The most recent M6 earthquake is the 2008 Wells, NV earthquake. It is important to consider the 150-year-long historical record in addressing earthquake monitoring along the Walker Lane and the populated areas of western Nevada and eastern California (dePolo, 2014). Table 3 and Figure 4 reflect the variation in tectonic settings that are monitored by NSL throughout Nevada and eastern California. Whereas the primary risk to Nevada citizens is associated with the Walker Lane, the 2008 Mw6 Wells earthquake in NE Nevada, demonstrates the potential for significant damaging earthquakes anywhere in the State.

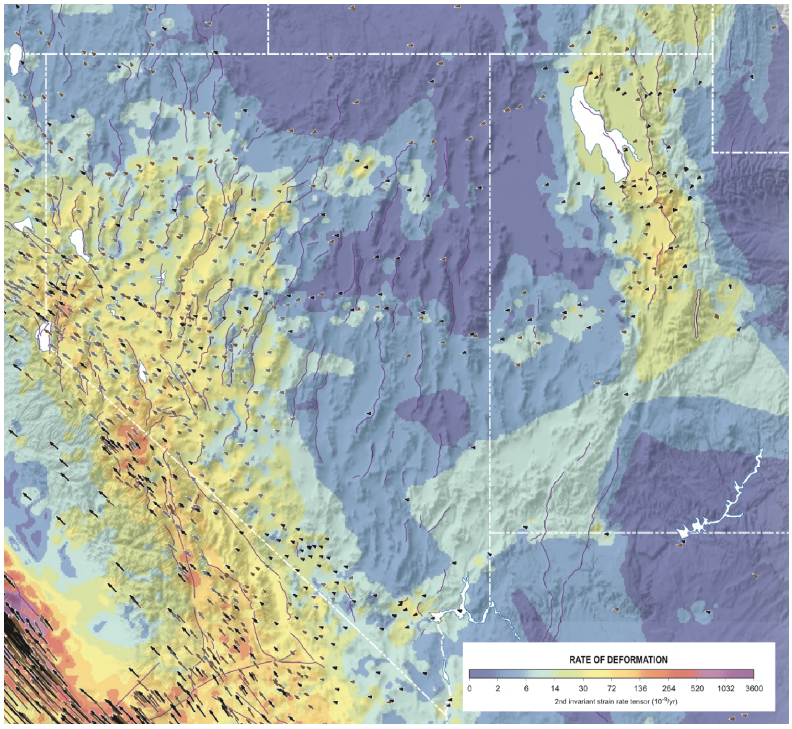

Figure 5. Basin and Range strain rate from GPS (Kreemer et al., 2013). Note the shear zone connecting the Eastern California Zone/Walker Lane through Las Vegas, NV to the Wasatch Zone, UT, as well as the high strain rates along the Walker Lane through the Reno-Tahoe area.

The seismicity (Fig. 2), seismicity rate (Fig. 3 and Table 1 and 2) and strain rate (Fig. 5) all highlight the unique nature of deformation in the Eastern California Shear Zone/Walker Lane deformation belt, relative to the Basin and Range proper (Kreemer et al., 2013). These rates seen in Tables 1 & 2 and Figures 2 & 3 are consistent with recent regional strain measurements from GPS (Kreemer et al., 2013), that correlate with seismicity rates, the National Seismic Hazard Map, and the relative numbers of earthquakes processed in routine operations. Another surprise from geodetic studies is the lack of deformation in the core of the Basin and Range, consistent with the behavior of an independent microplate. Because of this tectonic configuration, strain that is observed along the Wasatch Range front is transferred through a sinestral shear zone across southern Nevada and the Las Vegas region. Although the active faulting along the Wasatch range front is spectacular, a nearly equivalent amount of strain travels through southern Nevada near Las Vegas, and due to its strike-slip nature, is more muted topographically. Although both regions have more or less an equivalent hazard, strain in the Las Vegas region is more distributed relative to Salt Lake City. Nevertheless, recent paleoseismic work (Lamichhane et al., 2014) in the Las Vegas Valley has uncovered several faults with Holocene rupture; some of these very recent published results are reflected in the 2014 USGS hazard map (Petersen et al., 2014).

To further illustrate the seismicity rates, Figure 6 and 7 show the cumulative number of events located during routine processing during the past 5 years, and the magnitude progression (Magnitude ≥ 2), respectively. Seismic activity is fairly constant throughout the Nevada region during the reporting period (Fig. 6). The increase in activity in late-2014, early-2015 reflects the NW Nevada Sheldon earthquake sequence near the Oregon border (Ruhl et al., 2015).

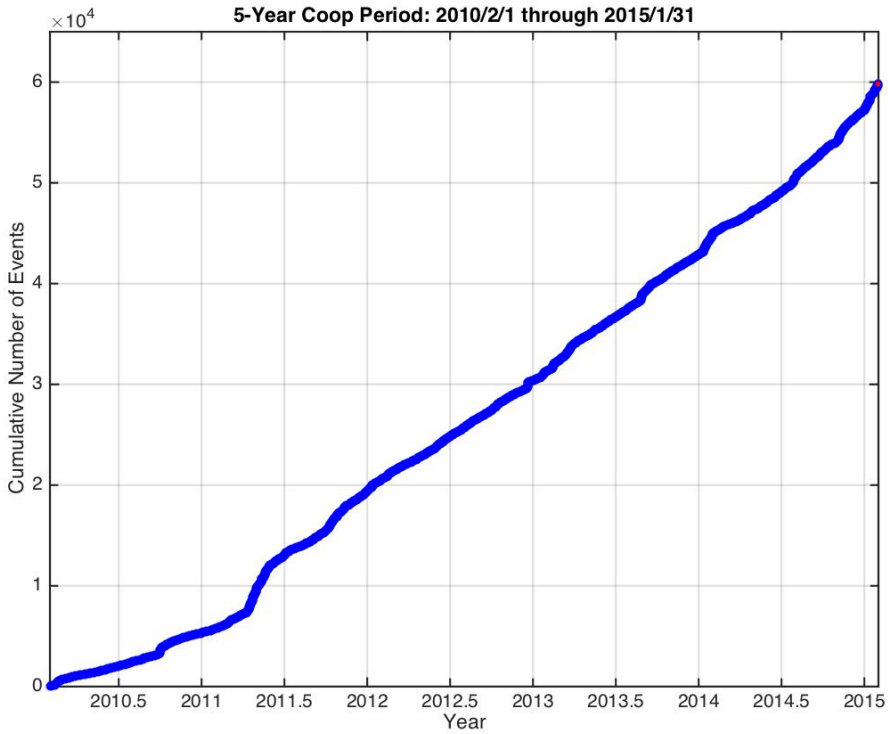

Figure 6. Cumulative number of events located by NSL during the 5-year period.

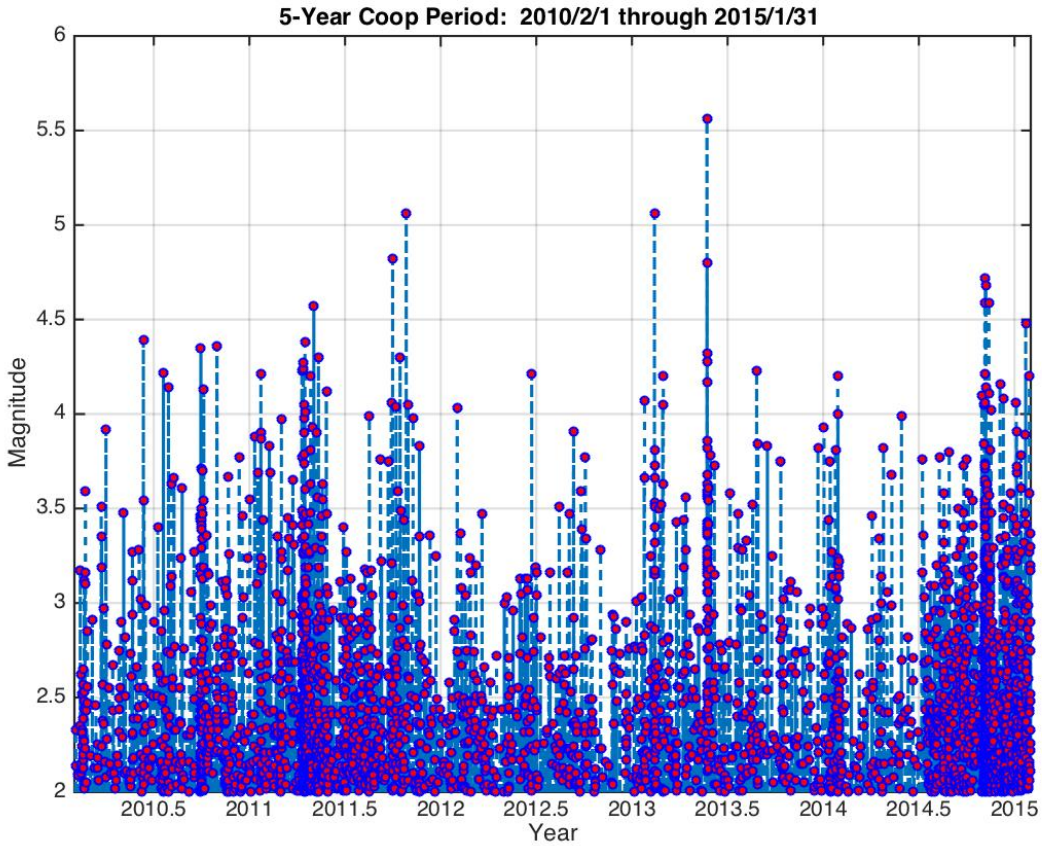

Figure 7. Magnitude progression for events shown in Figure 6.

Notable Earthquake Sequences and Station Installations:

NSL has extensive experience in deployment and management of portable digital instrumentation and telemetry systems, and has conducted numerous temporary station deployments in response to significant earthquakes. We integrate temporary earthquake response deployments with real-time telemetry, and this has been very successful in terms of data return and ease of station maintenance. All temporary portable telemetered data are provided in real-time to NEIC, IRIS DMC, and directly to participating networks via SEEDLink, when requested.

<u>2011-2012 Sierraville, California Deep Earthquake Sequence</u>

Over 2200 deep earthquakes (depths: 28.5-33 km) were located in a near 'repeat' of the 2003-2004 deep sequence under North Lake Tahoe (Smith et al., 2004). The earthquakes defined a N45°W striking 50°NE dipping 5x5 km structure (Smith, 2013). The events were interpreted, as was the 2003 Tahoe sequence, as a dike injection event at or near Moho depths. With NSF funding, NSL deployed four temporary digital broadband instruments in the source area. All data were delivered in real-time to NEIC and the IRIS data center. The sequence lasted for about 8 months.

2011 Hawthorne, Nevada Sequence

This energetic swarm of earthquakes about 30 km SW of Hawthorne, NV included nine earthquakes Magnitude ≥ 4 and fifty-nine Magnitude ≥ 3 events. Numerous events were felt in the community of Hawthorne and at nearby military facilities (Smith et al., 2011). NSL deployed four temporary telemetered broadband/accelerometer 6-channel seismographs in the near-source area. Moment tensor solutions and relocations following portable station deployment showed the sequence primarily consisted shallow normal faulting on multiple structures. All data were distributed in real-time to NEIC and to the IRIS Data Center. Over 5,000 earthquakes were located in the 2011 Hawthorne sequence.

2013 Lake Almanor, California Magnitude 5.7 and Aftershock Deployment

NSL installed three USGS NetQuakes instruments in support of Northern California network operations immediately following the earthquake. Data from these stations were the basis for studies of the 2013 Lake Almanor aftershock sequence. The sequence was outside of the NN authoritative reporting area, however NN network stations were critical for constraining earthquakes locations.

2013 Magnitude 5.1 Columbus Marsh Earthquake, West Central Nevada

The 2013 Columbus Marsh sequence was a classic mainshock-aftershock sequence as compared to some of the recent energetic swarms that have been experienced in Nevada. The earthquake occurred in a remote area and no temporary deployments were conducted. The earthquake is thought to have occurred on the Coaldale fault, an ENE striking high-angle structure. The main event showed left-lateral strike slip motion consistent with expected slip on the Coaldale fault.

2013 Magnitude 4.2 North Reno, Nevada Spanish Springs Earthquake

Through late 2012 and the 1st of half of 2013 a swarm of small earthquakes was recorded in the North Reno area that culminated in a Magnitude 4.2 earthquake. This event was felt throughout the city and resulted in minor damage. It was felt strongly in some unreinforced masonry structures on the University of Nevada Reno campus. Nearly 1400 earthquakes were located in the sequence, most very small that did not trigger the automatic systems. Prior to the Magnitude 4 event, NSL was active in notifying Emergency Managers and the public through media outlets on a regular basis regarding the state of the sequence. Some citizens, particularly in the north Reno area, took preparedness measures that most likely reduced non-structural damage.

2014-2015 NW Nevada Sheldon Refuge Earthquake Swarm

Seventeen earthquakes of Magnitude ≥ 4 have occurred in the Sheldon Refuge sequence in far NW Nevada since early July 2014. All of these were felt in the local farming communities and in Cedar City, CA; many were felt in Adel, OR. To date, ~200 Magnitude ≥ 3 earthquakes have been located in the Sheldon sequence. NSL has located 4936 events in the sequence with a completeness threshold of about Magnitude 1.5. The area is very remote and telemetry and access are difficult, but two portable instruments were installed in November 2014 on private property. A USGS NetQuakes instrument was installed near Vya, NV, and a portable digital station (Nanometrics Compact Seismometer), with cell telemetry through Adel, OR, was installed with the permission of a private land owner in Coleman Canyon, Nevada, about 15 km from the activity. The poor station coverage has limited our ability to develop accurate locations, but preliminary evidence suggests normal faulting on a SE dipping structure at mid-seismogenic depths (Ruhl et al., 2015). Over 60 moment tensor solutions have been developed

from the Sheldon sequence and these have been posted to the USGS ComCat archive. All data from temporary stations were provided in real-time to the USGS and to the IRIS data center. Temporary stations are still in place at the time of this report.

New Station Installations:

Over the past five years we have added 11 new broadband stations, and land-use permits are in process for the installation of several more. New broadband seismometers have been installed at legacy single-component analog sites, including CTC-North Lake Tahoe, CA, MPK-North Lake Tahoe, NV, LCH-Last Chance Range, CA, HEL-Hells Gate, CA, QSM-Queen of Sheba Mine, CA, GWY-Greenwater Valley, CA, and LHV-Little Huntoon Valley, NV. New station installs include: WDEM-Washoe County Division of Emergency Management, Reno, NV, REDF-Redfield Campus UNR south Reno, NV, SPR3-Spring Mountains near Ely in eastern Nevada, and COLR-Coleman Canyon, NW Nevada. This nearly matches the number of broadband installations under the USGS ARRA agreement. We also installed NetQuakes instruments in Reno, Carson City, Lake Tahoe, Las Vegas, and in eastern Nevada along the I-80 corridor (Fig. 8), as well as at Lake Almanor, CA in response to the 2013 Magnitude 5.6 earthquake.

Routine network maintenance and data center operations:

Routine Processing of Earthquakes and Event Response:

Due to approximately 12,000 earthquakes per year that are located within the network, earthquake processing demands attention, often on a 24/7 schedule during active swarms. Analysts and seismologists have remote access to event processing applications for off-hours earthquake response and routine analysis. NSL utilizes the Antelope seismic network software system; all daily processing and interaction with archived event parametric information and waveform data are conducted with Antelope tools. All event information is stored in the Antelope DataScope relational database for easy access and availability to other post-processing applications. Automatic event locations that meet certain phase, uncertainty, and geographic criteria are distributed in emails to the network staff, the public, and to the ComCat catalog. Phase data from automatic event 'origins' are processed through the USGS location routine HYPOINVERSE, as a confirmatory step, before final notifications, text messages, and QuakeML reports are generated. Location information for earthquakes of Magnitude ≥ 3 are also text-messaged to network staff and, if meeting more stringent criteria, are emailed to NSL notification subscribers (currently over 700 for the Nevada region). NSL staff respond to all Magnitude 3 and larger earthquakes 24/7 (at an average of 1.7/wk during the 5-year cooperative agreement period). In addition to reviewing all automatic locations, continuous waveform data near urban areas and in other regions of Nevada are scanned for events that may have been missed by the automatic system. In particular we have a goal of locating 'every' recognizable earthquake in the Reno-Tahoe-Carson City region. Despite reduced staffing levels, we have within the past year attempted to 'stay current' on event processing. Falling behind during very energetic swarms can create a significant backlog that may limit response capabilities to additional earthquake activity in the state; we have made progress and have 'stayed current' during the recent NW Nevada Sheldon Refuge swarm in addition to keeping up with regular Nevada activity.

For earthquakes of magnitude ~3.5 and larger moment tensor solutions are computed, submitted to ComCat and posted on the NSL web page. These are typically done during immediate event response. The system applies the MTINV code of Ichinose et al. (2014) to invert regional long-period surface waves for the moment tensor double-couple and non-double couple components. The software wrapper to MTINV developed at NSL implements a SOD request to the IRIS and NCEDC data centers for all broadband data and response information with a specified distance of the event, and pre-processes these

waveforms for MT inversion. Green's Functions for source-receiver paths are computed 'on-the-fly' using the wavenumber integration code of Zeng and Anderson (1995) and the US WUS velocity/attention model, requiring no need to maintain on-line libraries. In addition, since the data and station response information are maintained at national data centers, moment tensor solutions can be computed for any global event, given a velocity/attenuation model. NSL moment tensor solutions agree very well with St. Louis University (SLU) and UC Berkeley results. NSL has generated 200 moment tensor solutions since mid-2010 for Nevada and eastern California earthquakes. Results are maintained locally in the Datascope database and posted on the NSL web page, including images of waveform fits, double and non-double couple components, and beach ball images. Moment tensor solutions are also now being transmitted to ComCat.

Earthquakes with approximately 15 recognizable first motion polarities are processed for a short period focal mechanism solution with an NSL-developed, Python-based implementation of the USGS application HASH (Hardebeck and Shearer, 2002). This tool can be applied directly through Antelope during routine analysis or in post-processing from the database archive. Since implementation in 2012, 2908 short period focal mechanisms have been calculated for Nevada and eastern California earthquakes.

Post-processing tools have also been implemented to run USGS HYPODD (Waldhauser, 2001) directly from the Datascope database using both the Antelope PERL and MATLAB APIs. The PERL application pre-processes Antelope database information for HYPODD phase data and event association, and a MATLAB application performs waveform cross-correlations. This can be done on a routine basis but primarily has been used to identify structure in local ongoing swarms and aftershock sequences. HYPODD greatly improves routine event locations.

Data Center Operations and Network Operations:

NSL operates a statewide network of 149 ANSS-supported stations, spanning N-S for some 500 miles and E-W for about 300 miles in total coverage (Fig. 8). Communication to these stations is primarily provided through NSL's private, multi-use, IP communication backbone.

1. IP/Microwave Network and Telemetry: The NSL communications network has been radically overhauled over the 5-year period, with the majority of equipment and installation costs supported by other agencies and projects (not through ANSS). New digital network links, that have throughput up to 150 Mbps, have replaced antiquated analog baseband telemetry. This new high-bandwidth, multi-use system provides NSL with the capability to develop partnerships that were not possible with older analog communications systems. For instance, there has been a great deal of interest in the NSL fire camera initiative, that operates high definition Pan-Tilt-Zoom mountain top cameras at remote sites around the Tahoe basin and in remote areas of Nevada. These 1080p HD IR-capable cameras consume considerable communications resources (10-25 Mbps), which would not have been possible without a high-bandwidth network. These projects have been essential to the operation of the statewide seismic network; ANSS support alone is insufficient to maintain a statewide digital communications network, and thereby to maintain remote digital seismograph systems. These relationships and partner projects are essential for NSL in developing seismic network coverage in rural areas of the state, as well as improving monitoring in Las Vegas over the next five years.

The main microwave communications backbone trunk consists of 9 primary high-bandwidth IP back haul radio links. The entire IP wireless system is based on low cost radios/router boards. Diagnostics, for both the telemetry and remote digital stations, are managed under the Nagios public domain network software application. The NSL network operations staff is well versed in these systems for trouble shooting and preventative maintenance (e.g., all power system diagnostics have staff email notification thresholds). The communications network is scalable and includes significant telemetry link

redundancy and OSPF routing failover. Ubiquity/MikroTik radio systems are at or near commodity pricing and therefore the communication system is poised to incorporate any managed IP device, at low cost. With this expertise, NSL has developed important research relationships within the University system and with a number of federal and state agencies (e.g., DOE, NSF-EPSCoR, BLM, USFS), in what is developing into a unique multi-hazard system for first responders and researchers in a range of disciplines. Considering the large footprint of Nevada and eastern California, where access to the microwave is limited or would require prohibitive costs to expand, cellular technology (e.g., Verizon 3G dongles) is utilized, if available.

2. NSL Data Center, Hardware Systems, Software Development: The NSL data center provides acquisition headquarters for the Nevada Seismic Network, as well as home to a local archive of all seismic data from the NSL network. Data acquired through shared data sources from adjacent networks, and historical waveforms are also housed at the NSL data center. There have been many hardware and software improvements to data center over the past 5 years, in both networking and computing. While some of these upgrades and developments were specific projects undertaken to improve ANSS reporting capabilities, others were performed under separate sponsored contracts that have contributed to overall data center progress.

NSL was an early, if not the first, RSN to adopt the EIDS/EQXML reporting system. This replaced QDDS in July of 2010 as our production-level reporting interface, and was implemented in native EQXML, rather than simply XML-wrapped QDDS messages. The implementation included custom back-end programming to generate messages from database and real-time events, and route those messages through redundant EIDS instances and multiple ISPs.

In 2013, NSL was also an early, if not the first, RSN to adopt the PDL/QuakeML reporting system. This replaced EIDS/EQXML in November of 2013 as our production-level reporting interface. Again, the implementation included writing custom back-end software that not only interacts with our data store, but also creates custom QuakeML messages per the new USGS extensions to the QuakeML specification. Some of our work to include those extensions was submitted to, reviewed by, and implemented in the ObsPy seismic processing framework, which will facilitate QuakeML/USGS customizations for other regional and worldwide seismic networks. Since early 2014, we have generated QuakeML submissions for all event origins, phases, focal mechanisms, and moment tensor solutions, in near real-time, and have submitted these via the USGS Product Distribution Layer (PDL) software. We continue to monitor and debug our network to reduce the latency of our reports, and have worked internally and externally with the USGS to make this process efficient, effective, and as transparent as possible.

In early 2014, we integrated first-motion focal mechanism processing capability into our earthquake analysis workflow. This involved performing an audit of several existing focal mechanism algorithms and/or software projects, and choosing the best solution. We adopted the HASH method, refactored the entire existing Fortran code base, and integrated it into our analysts' workflow. Our software package is written in modern Fortran and Python, and not only provides the original HASH capability, but adds new functionality such as graphing, and allows greater interoperability with databases, messaging systems, web services, etc. This software is available to the public on GitHub and can be easily adapted by other networks.

Throughout the cooperative agreement period, NSL calculated moment tensor solutions for events greater than Magnitude ~3.5, using custom programs to run the MTINV software of Ichinose et al. (2014). From 2010 through 2013, these solutions were submitted to ANSS as a link to NSL's event-specific web page, and as EqXML messages through EIDS. In 2014 the solutions were reported as QuakeML through PDL. An up-to-date list of all solutions was available on the NSL website throughout the reporting period. NSL has computed about 200 moment tensor solutions during the past cooperative agreement period.

NSL uses Antelope's *dbbuild* program to generate tables for its meta-data database that is founded on the standard CSS3.0 data format. The *dbbuild* software is simple and effective, but we made significant progress in the way it is applied. In particular, we migrated from a system that relied on a per-station run to append a static database, to a full-blown regeneration of the entire database each time a change is made to the network. This allows much faster and more extensive edits to be made to our meta-data set, in a consistently reproducible way that can be easily learned and managed by other staff. Text files that contain the net, sta, chan, loc, and epoch information for each station were reformatted, organized, and placed under revision control. Custom programs were written to manage the regeneration process, and included functionality to merge other RSNs' Dataless SEED volumes into the final product.

In 2010, NSL began the process of migrating all of our services and applications from Solaris to Linux, including the Antelope seismic data acquisition and processing systems. This process is nearly complete for our critical systems, and will be fully complete and in production by mid-2015.

The NSL Reno Data Center's secondary power source consists of a three-phase, 20KW diesel generator on an automatic transfer switch, both of which are maintained by the UNR Facilities department. This configuration was unchanged during the cooperative period. In the data center itself, servers and networking equipment are now protected by three (3) rack-mounted UPSs in each of four (4) server racks. These units replaced an antiquated 'washing-machine-sized' UPS in early 2010. In 2012 and 2014, electrical circuits and breakers in the data center were reconfigured and upgraded to better distribute generator-backed circuits to the rack-mounted UPS units. Finally in 2014, we purchased additional battery and inverter equipment to construct a tertiary power backup for critical infrastructure that will allow production-level servers to withstand a generator failure for around 24 hours. This tertiary backup will be operational by the Fall of 2015.

With an antiquated air cooler that has no secondary power source, NSL settled on portable 120VAC cooling units for backup data center cooling. We installed two KwikCool units, each with 2.5 tons of cooling capacity. These are installed on dedicated circuits of the C-leg of the 20Kw diesel generator previously described. This is a temporary solution and NSL is still in need of a modern cooling infrastructure upgrade.

In 2012 we established an auxiliary data center at the Nevada System of Higher Education (NSHE) System Computing Services (SCS) on the University of Nevada Las Vegas campus in southern Nevada. This was not funded under USGS/ANSS Coop. support, but it does serve in dual capacity as a backup for our entire archive. More detail on this can be found in our upcoming Continuity of Operations Plan for 2015-2020.

Throughout most of the cooperative period, NSL used several different waveform export systems, including Antelope's *orb2orb* program and an Earthworm. In the last part of 2014, we migrated our waveform exports to a SEEDLink system implemented on an Amazon cloud-based, high-availability distribution server. One of the benefits of running in the cloud is that we can see exactly how much data is being uploaded and downloaded. NSL is currently exporting approximately 150GB of data per month -- essentially our entire ANSS network of weak motion (including broadband) and strong-motion instruments to other seismic networks.

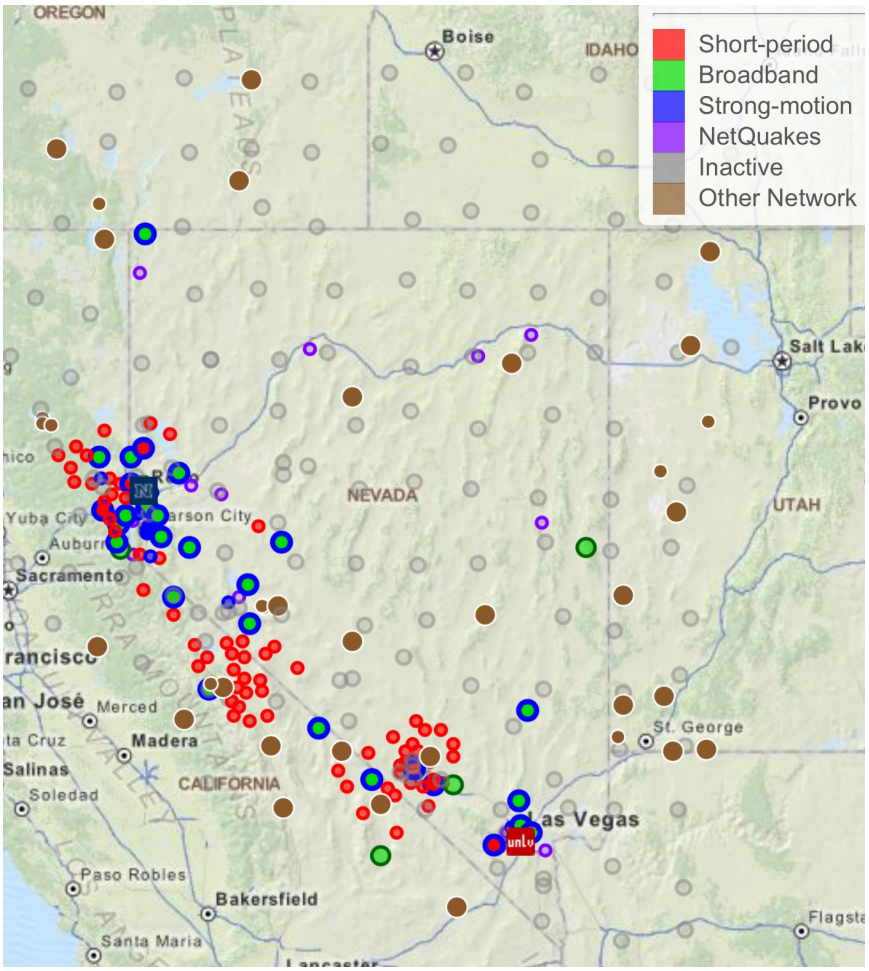

Figure 8. NN operated and acquired stations from partner networks (see legend for shared stations. Stations labeled as 'inactive', mostly TA and older NNSS area sites, have been permanently removed). Also shown are stations of the Central and Eastern NV network that will be managed on funding outside of this proposed effort (i.e., state of Nevada contribution).

Over the last five years we have completed three rounds of hardware upgrades and are now completing the third round of operating system upgrades. At this time we have not virtualized our computing environment and our storage environment is still running with direct-attached disks. In 2014 we decommissioned our magnetic-tape-based deep storage systems; all backups are now live on arrays of 4Tb hard disks. For our disk arrays, we are moving away from software/hardware RAID and toward ZFS file systems. We have automated some deployment and configuration with SaltStack software. This has sped up our process of putting new systems into production and made our operation more consistent. This automation is an ongoing process.

Real Time Integration of ANSS Regional and National Networks:

NSL data are provided in real-time via a SEEDLink server to Southern California, Northern California, the IRIS Data Center, USGS Menlo Park, UUSS, and NEIC. Other networks retrieve NSL data directly from IRIS. NSL receives data via SEEDLink from USGS Menlo Park, and Southern California; data from the Utah and University of Washington networks are received from the IRIS Data Center. These data from adjacent networks are critical for constraining the locations and magnitudes of

Nevada boundary events. Incorporating SEEDLink transfer has eliminated older Earthworm systems as well as several orb2orb processes, greatly simplifying data sharing.

Earthquake Notification Systems:

The use of multiple notification schemes provides assurance that staff and the public are aware of significant events in the region. NSL currently operates four such notification mechanisms, some internal and some for the public. These include 1) A Perl/Antelope-based email and text system for preliminary, internal event notification; 2) A similar email and text notification system also for internal use, for HYPOINVERSE-refined locations; 3) A public listserve email notification system for subscribers to (a) Earthquakes larger than M 3 in Nevada and (b) all earthquakes within the Reno-Tahoe-Carson City area; and 4) An internal Twitter service for tweeting our earthquake broadcast. This is an additional, easily-scalable reporting method, and a more accessible public interface for products than feeds or email lists. We currently serve 540 Twitter followers.

In addition to earthquake notifications, NSL also maintains a Nagios system for comprehensive network monitoring and problem notification. Nagios captures a vast amount of network data, e.g., data center computer status, data center security status, power system parameters throughout the network, and status on all IP devices, and issues internal email notifications to seismologists and technical staff following network events that need to be addressed.

During the 2010-2015 cooperative period, NSL has significantly improved its response, and quality and timeliness of real time earthquake products. We have also developed a much more effective dialog with the State and Local Emergency Management Community, providing real-time monitors at the State Division of Emergency Management and real-time earthquake notifications to government officials and the public. As mentioned above, we were early adopters of both generations of USGS reporting software. NSL has also significantly improved its 'off-hours' response performance, establishing 24/7 staff response to all $M \geq 3$ notifications (real or false) within the region. These responses include relocations, magnitude updates, MTs solutions, and reviewed ShakeMaps. Staff may continue into the evening hours keeping up with aftershock sequences (i.e., manual locations and magnitude updates), often times throughout the night. This dedication to earthquake response has paid off with a much higher profile and recognition of ANSS within the communities of Nevada. We will continue this progress into the new Co-Op period.

Data and Information Products:

Station Inventory and Metadata:

Station metadata for NN and SN network stations are available from IRIS, and updated after routine maintenance and/or new installs of all publicly available stations, including all ANSS support sites. Our local system metadata are typically updated within the same day. All station histories, during the past Co-Op, have been updated and are mostly complete and available on the 'discoverable' ftp site. Some historical metadata are not yet complete (e.g., some pre-2000 station metadata). This will be completed in the current Co-Op.

Distribution of Earthquake Products:

NSL has been submitting data products via PDL since 2013. We currently report origin, phase, moment tensor, and focal mechanism data in QuakeML format for all new events, automatic and reviewed. We are prepared to begin sending back-catalog data in this format when a bulk ComCat server is available. The underlying platform is a software package, developed at NSL, to respond to database

events (i.e., automatic and reviewed locations, reviewed MTs and short-period mechanisms) and produce a PDL QuakeML message.

ShakeMap:

NSL have several staff members that regularly generate ShakeMaps for routine processing and scenarios for research and preparedness applications. We automatically generate ShakeMaps for events M > 3.2. We maintain the current version of ShakeMap software and refine configuration and parameters that are shared with other networks. ShakeMaps are delivered in real-time, and revised versions, to NEIC and also archived at NSL (with selected scenarios).

Post-Earthquake Reporting:

Automated systems develop preliminary locations and magnitudes that are posted to ComCat via PDL. Preliminary locations and magnitudes are also distributed to subscribers to NSL automatic notifications (there are currently about 725 subscribers). Automated systems also generate email and text messages to staff for 24/7 response. Post event reporting for M ≥ 3 earthquakes include immediate reviews, relocations, and update magnitudes. NSL also computes MTs for M ≥ 3.5 that are posted to ComCat. ShakeMaps are automatically computed and delivered from M ≥ 3.5 and upon event review. For significant events in urban or populated area, NSL provides a summary to State and local emergency managers, within that specific jurisdiction. The level and quality of information exchange between NSL seismologist(s) and state and local emergency managers has been improved during this Co-Op cycle.

Participation Policy**:** As a cooperating regional seismic network within the IMW region, NSL is an active participant in ANSS. Although an IMW member, NSL also operates and maintains a significant number of stations in eastern California that are used by the California Integrated Seismic Network (CISN). NSL reports earthquakes in the eastern Sierra region to ComCat, as a contributor. NSL provides real-time data from many Nevada and all eastern California stations directly to CISN, and NSL data, including strong motion data, are archived in real-time at the IRIS data center. NSL operated station data provided to CalTech, Menlo Park USGS, and UC Berkeley are archived at Caltech and NCEDC. NSL regularly notifies the National Earthquake Information Center (NEIC) in Golden, Colorado, of local system issues that may affect reporting to allow/notify NEIC to assume regional reporting, if necessary, in the NSL authoritative polygon. Earthworm feeds, used for data exchange have been discontinued, and replaced with equivalent SEEDLink server protocols; this will allow access to NSMP data, assure NEIC receives all requested waveforms directly from NSL, and will improve systems for data sharing with CISN, UU and UW networks.

Dissemination of Information and Data (NSL Website)

NSL maintains its own public website (www.seismo.unr.edu) for the benefit of the citizens of Nevada and Eastern California. The site contains verified automatic and manual earthquake solutions, in map and list view. Additional information, including moment tensor solutions, waveform record sections, ShakeMaps, and historical seismicity, is posted for each event. An interactive map of current and past stations that NSL uses for earthquake detection and location is also available from the main page. The ANSS/USGS partnership is posted directly on the main page. The web site includes information on earthquake preparedness, active research projects, and up-to-date announcements on significant earthquake activity. It also hosts the sign-up mechanism for the public to receive real-time notifications, as described above. Our web site and public/agency/media event notifications have become an expected service from NSL for local and remote communities.

Web Site Details

- **Computed hypocenters and magnitudes**: "Earthquake" section (http://www.seismo.unr.edu/Earthquake): Shows an interactive map and list views of the Nevada Broadcast of Earthquakes, our regional broadcast of events occurring within the past weeks and months. These views contain links to individual event pages that list hypocenter parameters and additional

information on an event, such as event type and review status, along with more recent activity within 60 kilometers (the University of Washington has modeled their web site earthquake information from NSL format for presenting current information in map views).

- **The network's monitoring objectives in the context of the ANSS:** "About" section (http://www.seismo.unr.edu/About): Explains NSL's historical role in monitoring hazards for the state and as a part of the larger ANSS national system.

- **The scope of coordination with other monitoring networks:** All relevant sections reference and credit neighboring stations and networks where appropriate. For example, stations from other networks (see brown dots, Fig. 6) used for NSL hypocenter locations are clearly labeled as such on our station map.

- **Maps and lists of stations used in routine monitoring.** "Monitoring" section (http://www.seismo.unr.edu/Monitoring): Shows interactive map and list views of stations that NSL maintains, as well as additional stations used for refining hypocenters and moment tensor solutions. These views contain links to our public metadata holdings at IRIS.

- **Links to earthquake products and network services.** See (1) under "Earthquake" section and Event pages. Other tabs on these pages provide views of event waveforms, moment tensor solutions, and additional graphs of recent historical seismicity. In addition, we provide links to additional event products, i.e., ShakeMaps, when available, and to other sites, i.e., USGS "Did You Feel It?" when appropriate.

- **Acknowledgement of participation in ANSS and support from USGS with links to EHP and ANSS webpages.** Links to USGS, ANSS, and EHP can be found on our home page, and additional pages where appropriate.

- **Partnering networks and archives that receive waveform data and earthquake information products.** "Links" section (http://www.seismo.unr.edu/Links): Contains links to various related and partner organizations. Due to our various agreements with private partners, this is not a complete list, and we do not currently state which groups receive data from NSL. Expanding our section to include other specific RSN's who receive our data is a future possibility.

All data collected under the ANSS network are publically available, and NSL will accommodate any specific requests for real-tine data feeds within its current sharing capabilities (these capabilities now include cloud based SEEDlink connectivity). Currently, all waveform data are available at the IRIS DMC and a subset is available at the NCEDC.

Related Efforts

NSL's reliable IP communications backbone had been lead by staff innovation in implementing unique IP radio systems. This microwave network is the cornerstone for our earthquake monitoring effort as well as for many related monitoring efforts for climate and fire. The broad capabilities of the Antelope software system, have to been the key to supplemental network operations funding to bridge shortfalls and diminishing budgets for regional earthquake monitoring. A key partner has been NSTec on the Nevada National Security Site (NNSS). NSL provides support for the Source Physics Experiment, and operates eight regional seismic monitoring stations supported by NSTec on NNSS (data provided in real-time to the IRIS DMC). Also NSL has received support through the Nevada NSF-EPSCoR Climate/Energy Programs, the State of Nevada Knowledge Fund (primarily a UAV program requiring

innovative high-bandwidth communications development), the Nevada Division of Emergency Management (support for acquisition of broadband sensors for eastern and central Nevada), NSF First Responder Grant (NSL is a small member of the team providing innovative communications), the Nevada Paiute Tribal Community (seismograph support and developing programs in communications support for tribal emergency managers in remote areas of the state, remote learning, and telemedicine), the Lake Tahoe Fire Management District (HD Fire Cameras in the Lake Tahoe Basin), the Bureau of Land Management (implementation of communications and Fire Cameras in central and eastern Nevada), and mining interests in central Nevada. All of these efforts indirectly allow NSL to expand statewide seismic monitoring through extending communications systems.

Great Nevada ShakeOut: Year Five Progress and Assessment Report: (prepared by Diane M. dePolo)

The Great Nevada ShakeOut began in 2010 when Nevada joined California in the annual earthquake drill (first state to join California). The ShakeOut has grown in number of participants and breadth of participation and has become the number one outreach tool for earthquake preparedness in Nevada. The drill is an opportunity to engage Nevadans in earthquake preparedness and mitigation measures and to highlight earthquake hazards in Nevada. The ShakeOut is critical for a state like Nevada where relatively infrequent, but high consequence earthquakes occur. Recent seismic activity has been far below the rate of large, damaging earthquakes of the late 1800's and first half of 1900's. Before the 1960s, many major Nevada earthquakes were temporally clustered (Fig. 4). There were over 20 damaging events between1857 and 1960, but only one magnitude 6 between 1960 and 2014.

NEVADA ShakeOut Participant Totals	2010	2011	2012	2013	2014
CATEGORY					
Individuals/Families	183	316	705	580	417
Childcare and Pre-Schools	113	724	876	856	1,171
K-12 Schools and Districts	92,110	52,329	469,520	482,385	484,376
Colleges and Universities	20,067	51,471	25,752	54,999	55,062
Local Government	26	1,244	7,117	9,175	15,157
State Government	246	270	177	776	1,679
Federal Government (Including Military)	10	120	309	94	569
Tribes	15	435	677	583	498
Businesses	22	11,308	5,253	6,296	3,531
Hotels and Other Lodgings	0	0	0	0	0
Healthcare	2	4,170	4,979	8,443	5,930
Senior Facilities/Communities	0	0	230	200	0
Disability/AFN Organizations	0	0	0	0	0
Non-Profit Organizations	25	711	647	198	1000

Neighborhood Groups	**0**	**0**	**215**	**75**	**0**
Preparedness Organizations	**0**	**30**	**15**	**41**	**205**
Faith-based Organizations	**0**	**0**	**0**	**1,500**	**1,500**
Museums, Libraries, Parks, etc.	**0**	**12**	**2**	**0**	**0**
Volunteer/Service Clubs	**0**	**0**	**0**	**0**	**0**
Youth Organizations	**0**	**0**	**45**	**15**	**130**
Animal Shelter/Service Providers	**0**	**0**	**0**	**0**	**0**
Agriculture/Livestock	**0**	**20**	**20**	**0**	**0**
Volunteer Radio Groups	**15**	**20**	**0**	**35**	**50**
Science/Engineering Organizations	**0**	**5**	**14**	**19**	**0**
Media Organizations	**0**	**92**	**90**	**21**	**11**
Other	**0**	**0**	**32**	**145**	**208**
TOTAL	**112,834**	**123,277**	**516,675**	**566,436**	**571,494**

Seismic Network ANSS Performance Self Rating:

Question	Explanation (if needed)
1. What is the minimum magnitude detection threshold for the best-instrumented part of your network?	0.0, Reno-Carson City urban corridor
2. What is the typical hypocentral location accuracy for earthquakes occurring within your network? Is it the same for automated vs. reviewed?	Automatics: 1.7 km median epicentral, 2.5 km depth inside polygon of stations; reviewed are better.
3. Does your network report automated earthquake locations into EIDS? If yes, how long does it take?	Report on PDL, 2.5 to 4.0 minutes
4. Does your network report analyst-reviewed earthquake locations for all quakes into EIDS (i.e., the little ones)?	Yes. Processing delay is function of magnitude. M2+ is normally same day; smaller triggered events <5 days; manual review for smaller events can take longer.
5. Does your network have 24/7 duty seismologists who review real-time earthquake locations above some magnitude? If yes, what magnitude and how long does it take?	Yes. M3.0+ confirmation typically in 10 minutes and preliminary relocation in 30-45 min.
6. Describe the velocity model used to locate earthquakes in your network (1-D, multiple models, 3-D). Does it differ for automated vs. reviewed?	Automatic: 1-D Review phase: multiple 1-D models.

Seismic Network ANSS Performance Self Rating:

Question	Explanation (if needed)
7. What software/program does your network use to locate earthquakes? Does it differ for automated vs. reviewed?	Automated: *orbassoc* and *hypoinverse* Reviewed: *dblocsat* within *dbloc2*
8. What magnitudes does your network routinely report in real time (Md, ML, Me, Mw, Ms, etc.)? How long does it take to compute them?	ML in real time; 2.5 to 4 minutes; Mw manually for M3.5+, computed automatically but shipped after review.
9. Does your network archive phase information at a datacenter? If yes, how long is the delay to report? Where is the information archived?	Phase information provided with automatic and reviewed solutions; QuakeML format via PDL; archive at COMCAT
10. What is the date of the most recent event you have contributed to the ANSS catalog? If yes, how long is the delay to report? In what year does archiving begin?	ANSS catalog is updated 2x per day. Archive begins October 1, 2000; number of stations has increased over time; all now.
11. Where is the permanent archive of seismic waveform data from your network? If yes, describe what type of channels (e.g., EH, HH, HN) and how long is the delay to report? In what year does archiving begin?	Waveforms at IRIS DMC. Channels: EH., HH., HG., HN.
14. Does your system compute focal mechanisms? If yes, what type (first motion, moment tensor). In real-time? Do you archive them at a public datacenter?	Some. First motion FMs for events with sufficient phases; moment tensor FMs above ~M3.5; Mw and first motion FMs sent to COMCAT
15. Does your system automatically distribute email to the public in near real-time for significant events? If yes, do you offer a website where they can sign up? What is the URL?	Yes. URL: www.seismo.unr.edu, link entitled "Sign up to receive earthquake notifications"
16. Does your system automatically distribute alphanumeric pages to the public in near real-time for significant events? If yes, do you offer a website where they can sign up? What is the URL?	Notifications only by email
17. Does your system automatically compute ShakeMaps and make them publicly available? If so, how long does it take?	Yes; takes 7-10 minutes from origin (automatic); reviewed event ShakeMaps triggered manually in processing stream.
18. Is your processing system hardened? (i.e., fault-tolerant, with redundant computers, UPS, back-up generator & fuel)?	Redundant power with generator, backup cooling. Warm spare acquisition machines; redundant location and magnitude; new switches remove some weak campus links.
19. What is your network's total data volume (mbytes/day)? Specify how the estimate was made (e.g., data rate or disk storage) and if the data is compressed or not.	3.4Gb/day, based on sampled 2014 actual volumes
20. What is your network's total data volume (mbytes/year to archive)? If different from the daily volume times 365, explain the difference (e.g., reformatted, compressed, or edited).	1.2Tb/yr

Seismic Network ANSS Performance Self Rating:

Question	Explanation (if needed)

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